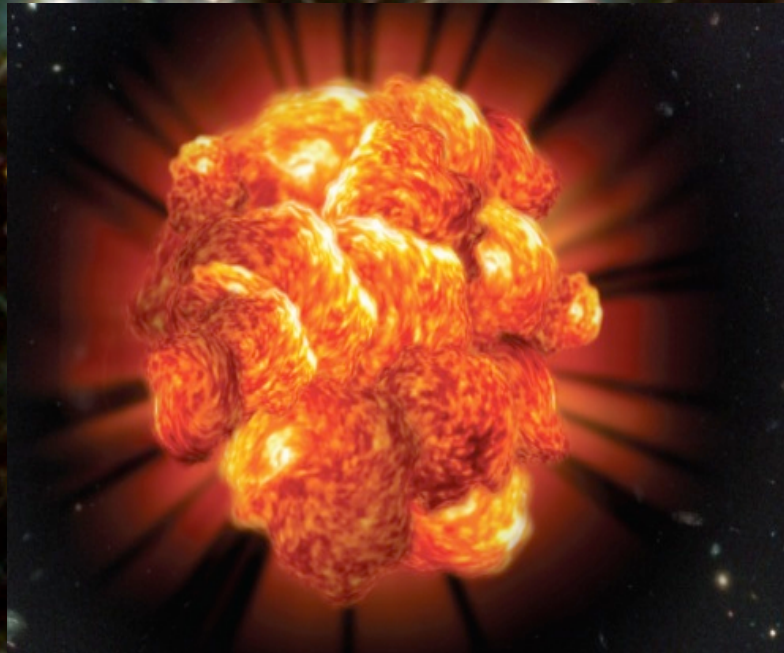


# Pair-Instability Explosions: do they happen in nature?



Avishay Gal-Yam,  
Weizmann Institute  
Stockholm 2011

# The Core-Collapse Spectrum

Lower mass limit unclear:

<7..11 solar; stable C/O core



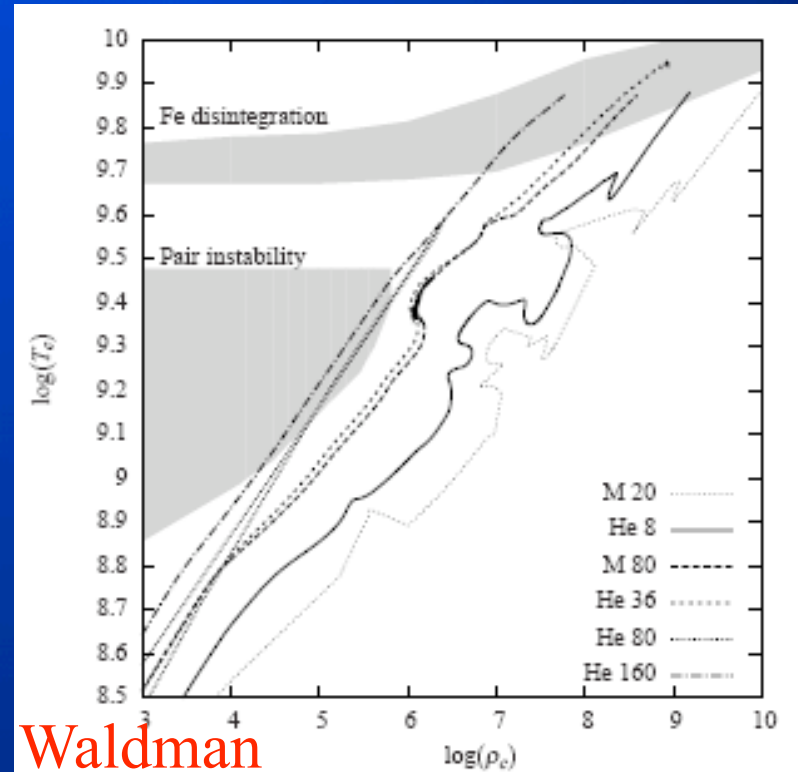
M: 7-11    M: 8-16    M: 17-25    M: 25-30    M: 40-50    M: 50-150    M> 150



# Pair Instability Supernovae (PISNE)

(Shaviv & Rakavi 1967; Barkat, Rakavi & Sack 1967 ; Heger & Woosley 2002; Waldman 2008 ...)

- \* Helium cores above  $\sim 50$  solar masses become pair unstable
- \* In these low-density high-T cores,  $\gamma\gamma \rightarrow e^+e^-$  wins over oxygen ignition, heat is converted to mass and implosion follows
- \* Inertial oxygen ignition leads to explosion and full disruption
- \* “This is a uniquely calculable process” (Heger & Woosley 2002); “this is a trivial calculation” (Barkat 2009); “Pretty neat homework problem” (Gal-Yam 1996)

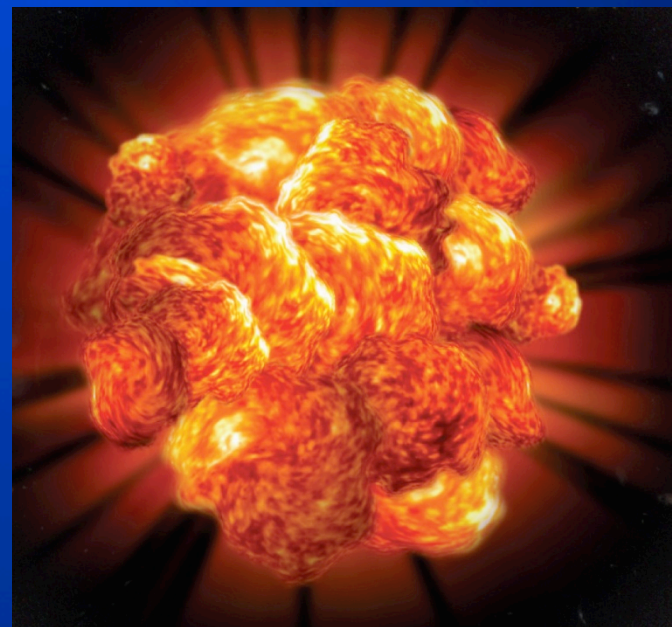


“Smoking gun”:

Core mass  $> 50$  solar

# Pair Instability Supernovae (PISNe)

- \* Helium cores above the threshold robustly explode
- \* PISNe care not for metallicity, but for mass loss
- \* PISNe progenitors seem not to exist in our Galaxy – require  $M > 140$  solar - (though transitional pulsational events might)
- \* At early Universe,  $M \sim 1000$  stars may have existed





# SN 2007bi=SNF20070406-008

(PTF “dry run”)

- \* Type Ic SN (no H, He).

No interaction, no dust,

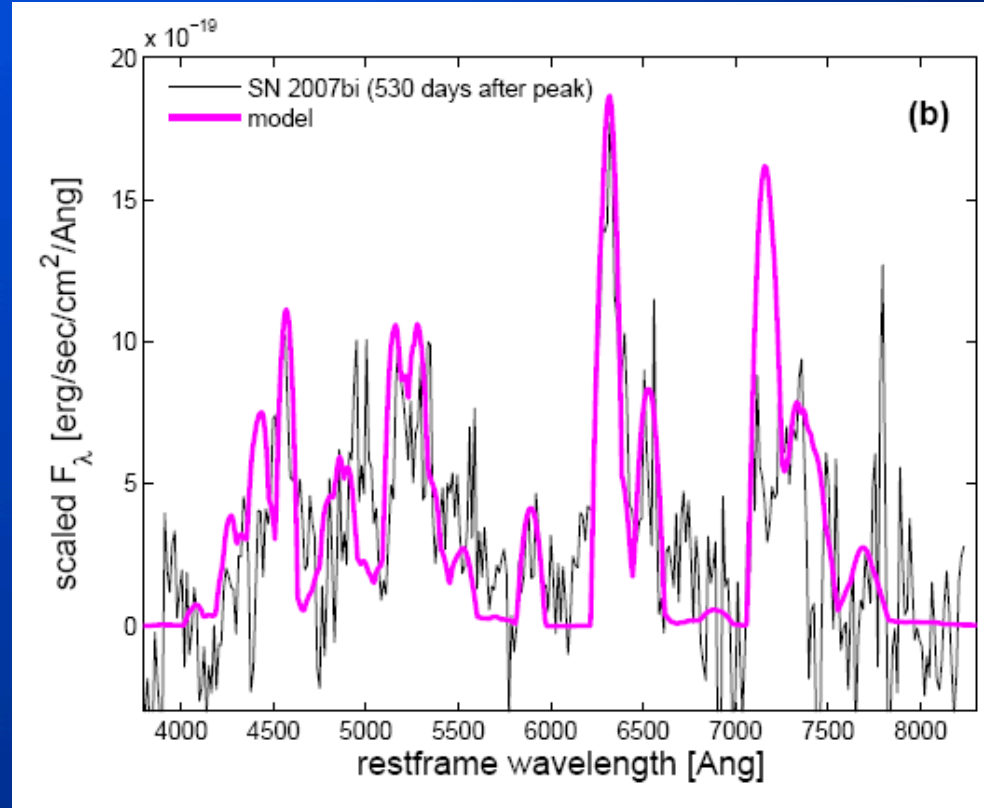
$v=12000$  km/s

- \* Luminous peak (-21.3),  
slow rise ( $\sim 77$  days),  $^{56}\text{Co}$   
decay

- \* ejected mass  $\sim 100$  solar,  
 $E_k \sim 1e53$ , 4-11 solar masses  
of  $^{56}\text{Ni}$  (87A)

- \* Well-fit by models (Kasen)

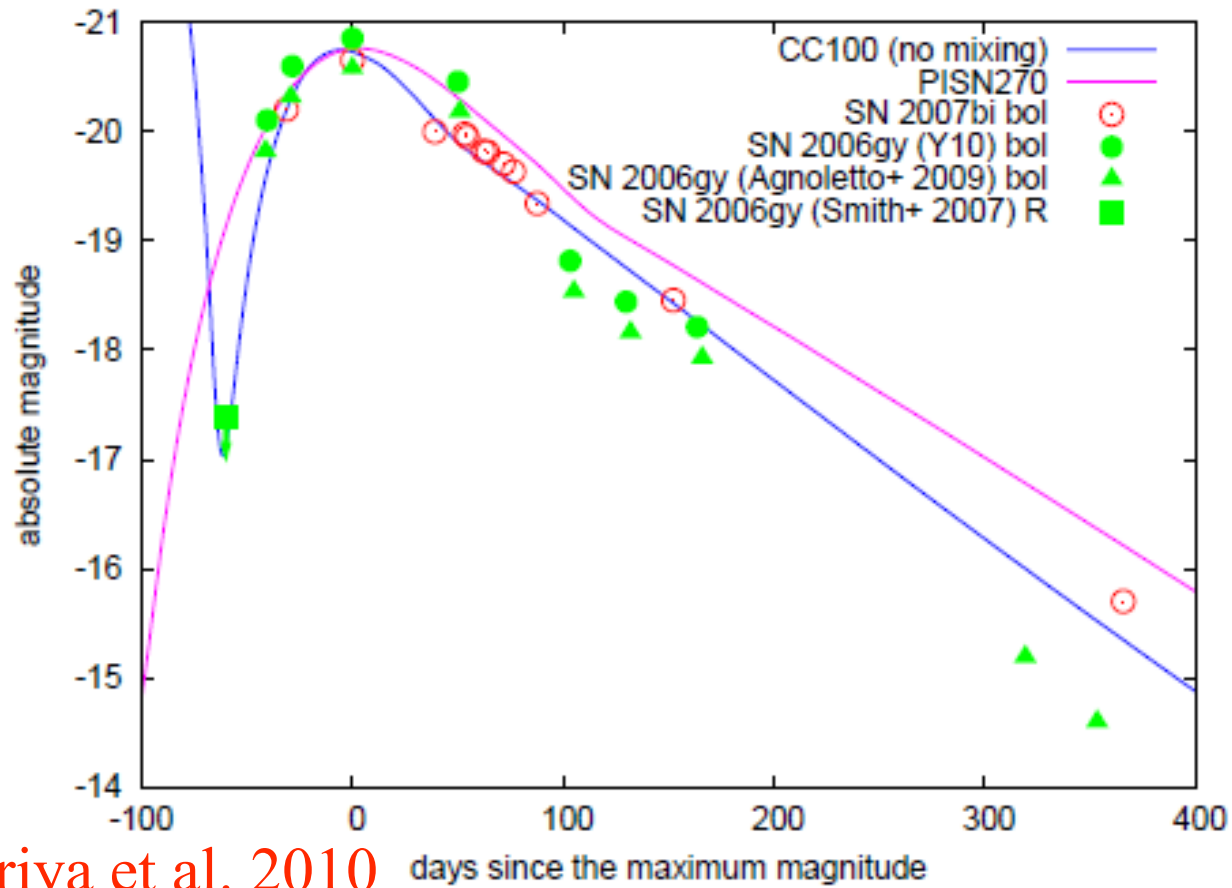
- \* Nebular spectra: 4-6 solar  
mass of  $^{56}\text{Ni}$ ;  $>50$  solar total  
(Direct comparison with 98bw; Mazzali models)



**Core mass  $> 50$  robustly established;**

Gal-Yam et al. 2009, Nature, 462, 624

# Alternative model?



Moriya et al. 2010

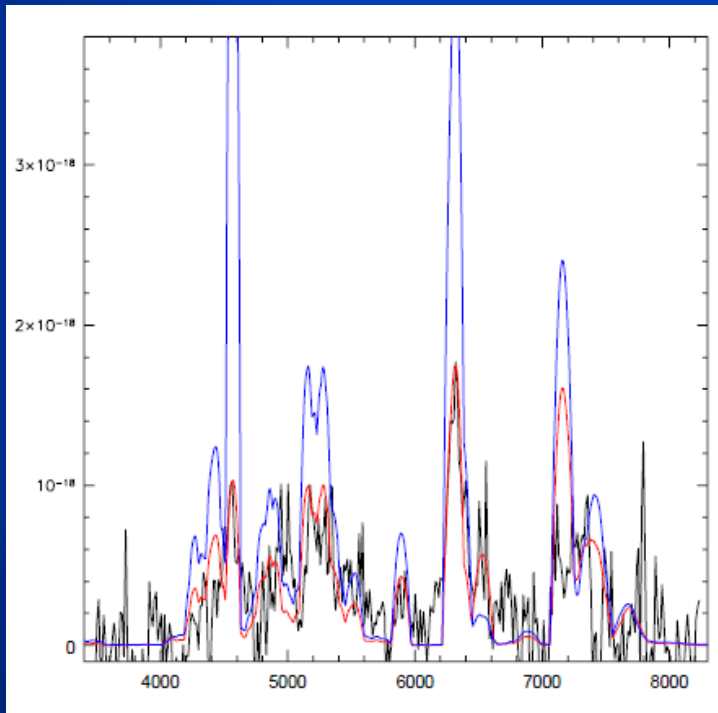
# Alternative model?

TABLE 1  
THE AMOUNT OF ELEMENTS CONTAINED IN THE EJECTA

$^{12}\text{C}$	$^{16}\text{O}$	$^{20}\text{Ne}$	$^{24}\text{Mg}$	$^{28}\text{Si}$	$^{32}\text{S}$	$^{36}\text{Ar}$	$^{40}\text{Ca}$	$^{56}\text{Ni}$
1.4	18.7	1.4	1.5	5.1	2.7	0.5	0.4	6.1

NOTE. — Units:  $M_{\odot}$

Moriya et al. 2010



Same amount of  $^{56}\text{Ni}$  within a smaller total ejecta mass: emission lines too strong.

CC model cannot explain SN 2007bi spectra



# Implications for mass loss

Table 1. The range of MS mass for PI and CC SN models appropriate for SN 2007bi deduced from the mass range of the CO core and the surface He abundance. The ratio of the probability of explosion as a PI SN to explosion as a CC SN for SN 2007bi,  $r_{\text{PI/CC}}$ , is also listed (see Section 4).

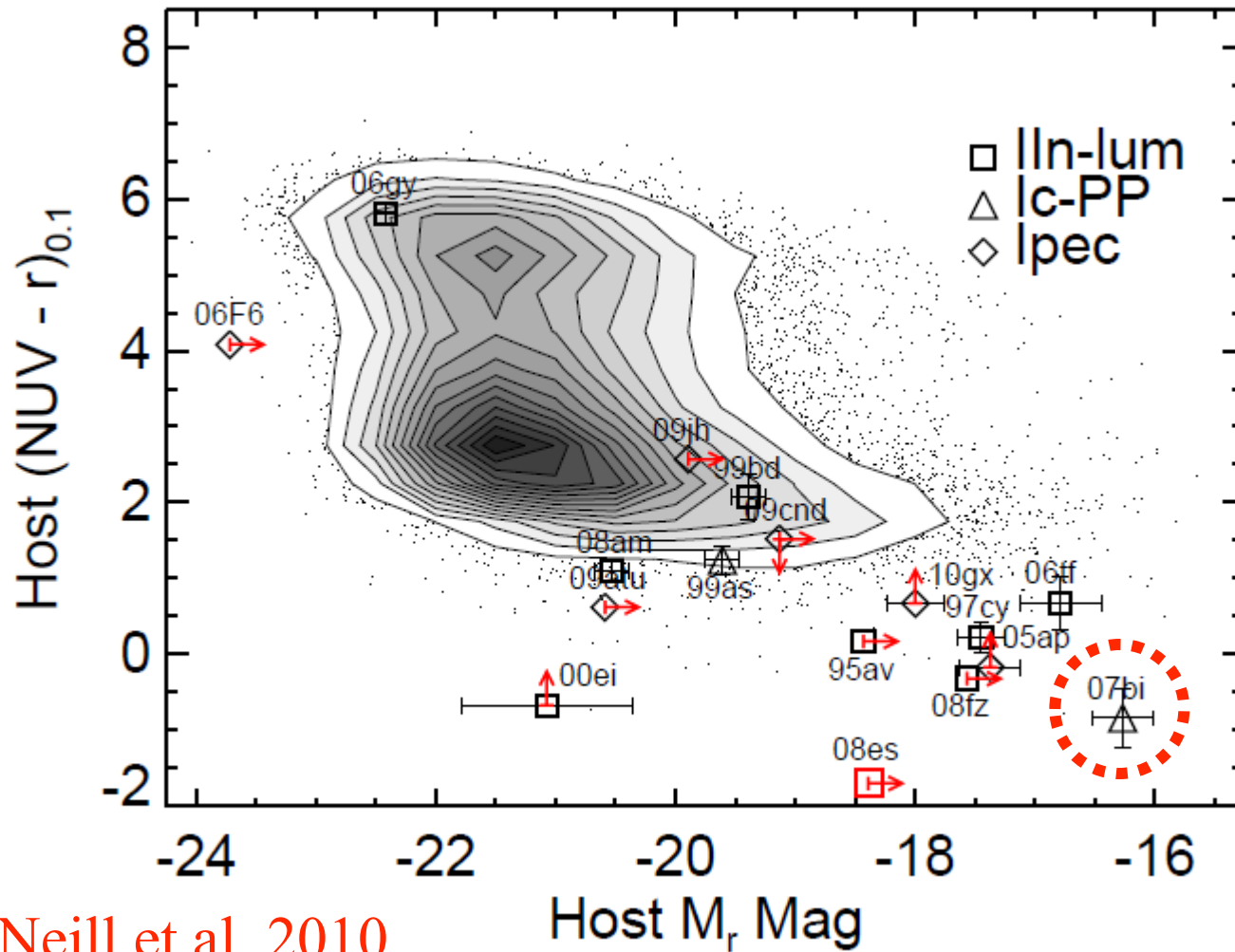
Condition	PI SN ( $M_{\odot}$ )	CC SN ( $M_{\odot}$ )	$r_{\text{PI/CC}}$
Case A			
$M(\text{He}) \leq 0.5M_{\odot}$	—	110 – 120	0
$M(\text{He}) \leq 1.5M_{\odot}$ or $Y_{\text{H}} \leq 0.5$	515 – 575	110 – 280	0.024
Case B			
$M(\text{He}) \leq 0.5M_{\odot}$	—	110 – 115	0
$M(\text{He}) \leq 1.5M_{\odot}$ or $Y_{\text{H}} \leq 0.5$	—	110 – 500	0
Case C			
$M(\text{He}) \leq 0.5M_{\odot}$	—	—	—
$M(\text{He}) \leq 1.5M_{\odot}$ or $Y_{\text{H}} \leq 0.5$	310 – 350	135 – 170	0.19

Yoshida & Umeda 2011

If CC model ruled out, either we have found stars with initial mass  $> 500$  solar, or standard mass loss theory needs to be revised

**In any case, PISNe likely exist at high- $z$**

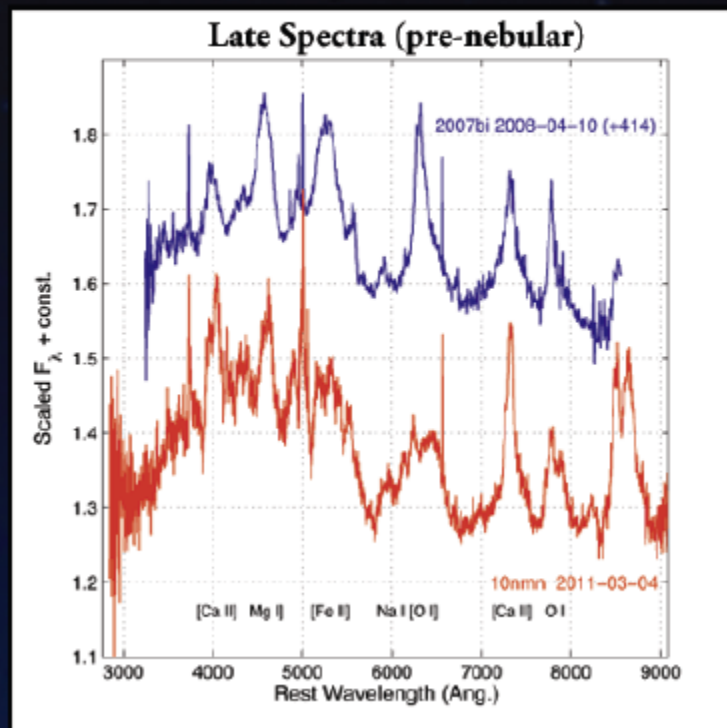
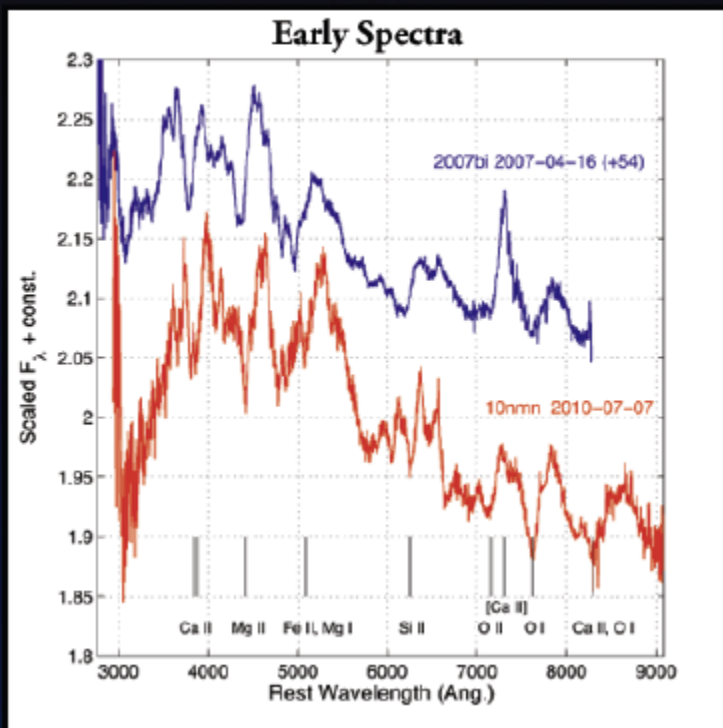
# Extreme host



# PTF 10nmn: new results from PTF

(Yaron)

## Comparison of Spectra: 10nmn vs. 2007bi

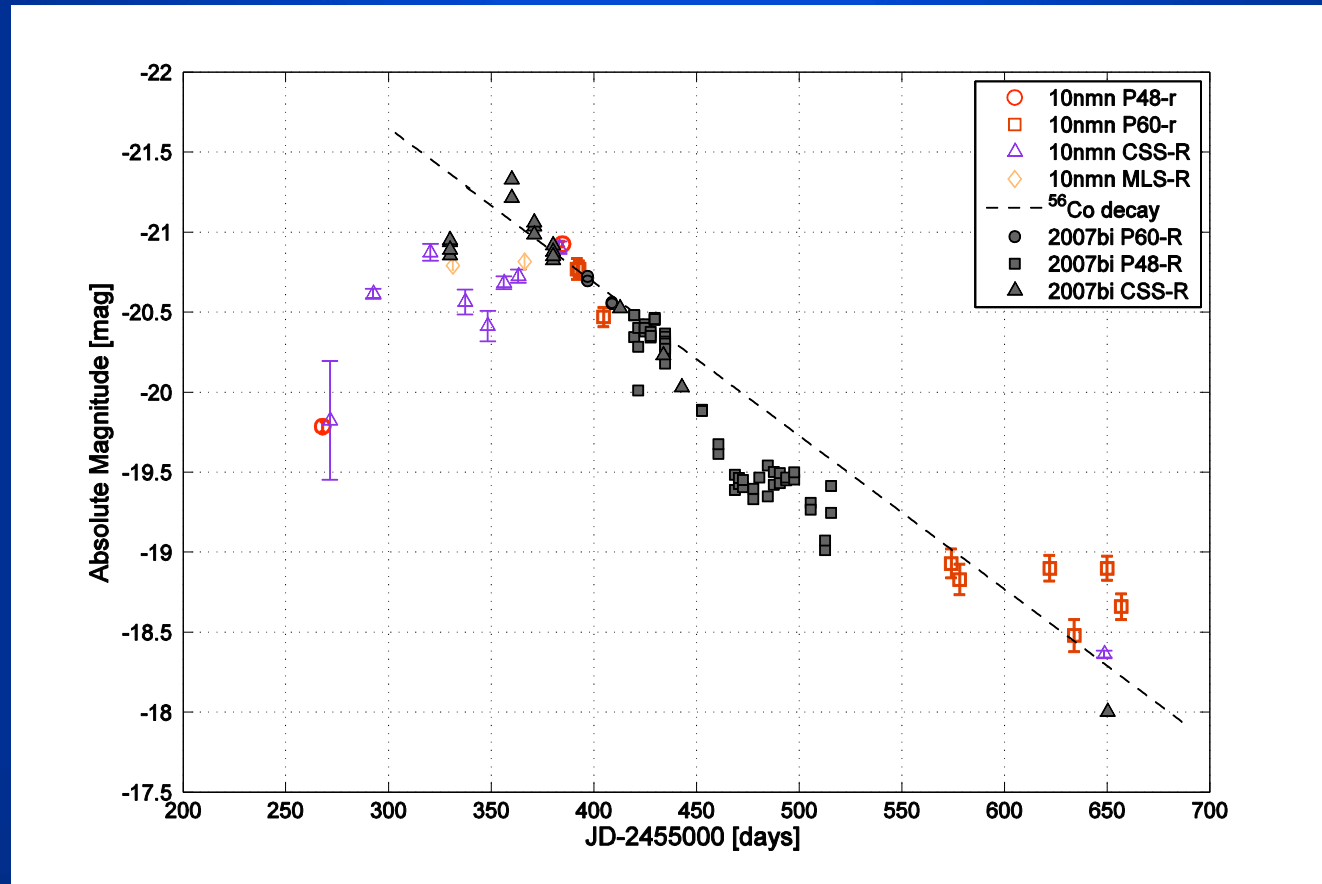


- SN 2007bi lookalike



# PTF 10nmn: new results from PTF

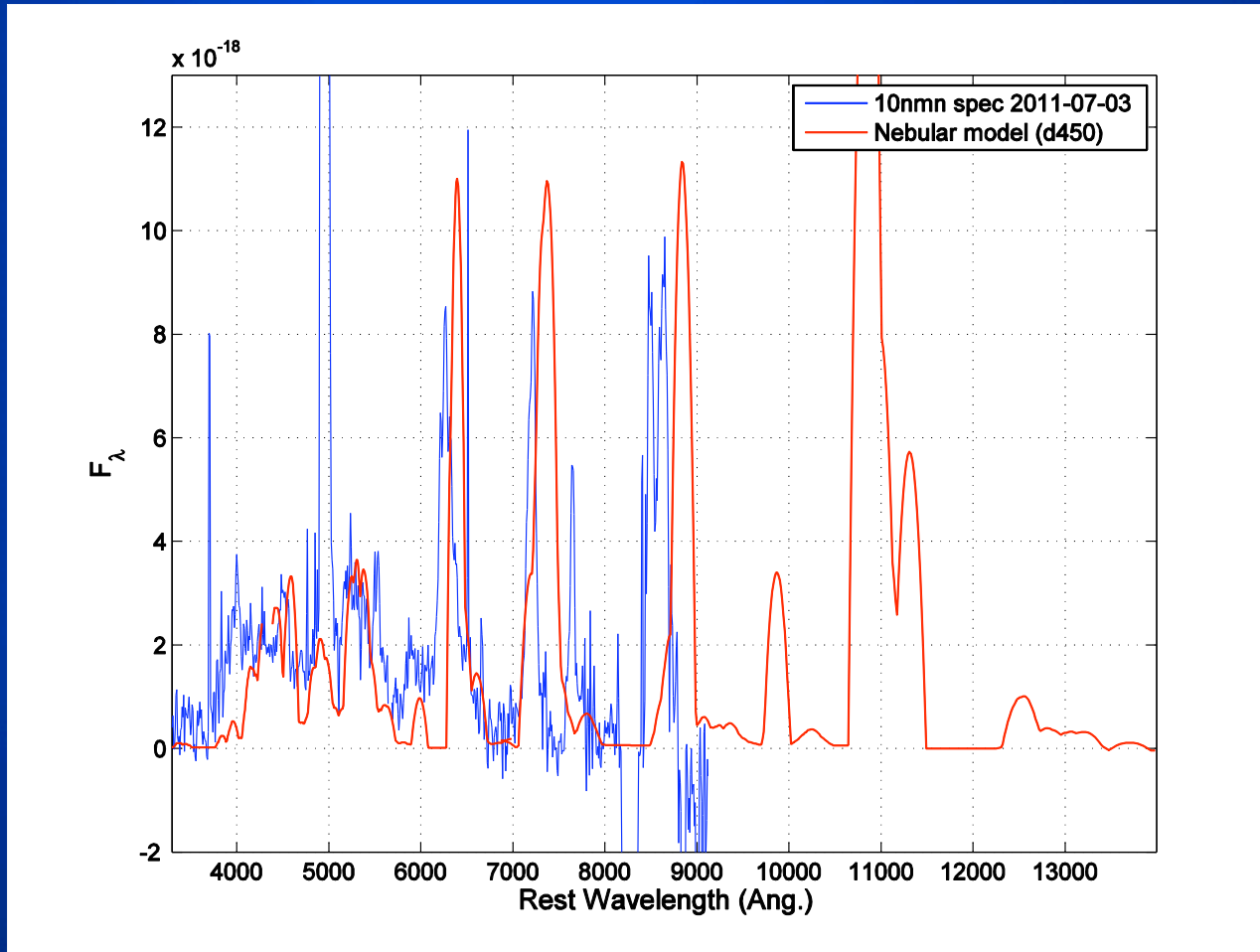
(Yaron)



- Complicated light curve, but slow rise (in favor of PISN)

# PTF 10nmn: new results from PTF

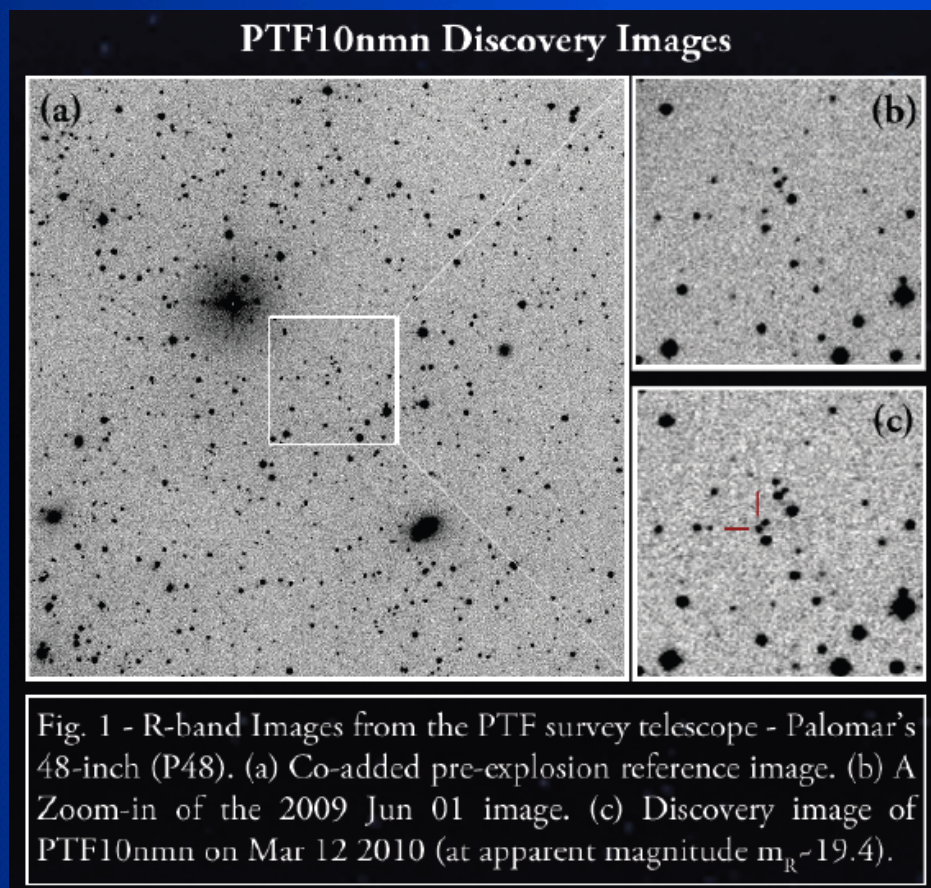
(Yaron)



- Nebular spectrum: Ni=5, total=100m lots of C/O (and Ca); IR: an opportunity not to be missed!

# PTF 10nmn: new results from PTF

(Yaron)



- Host: another dwarf ( $< \text{LMC}$ )



# PTF 10nmn: new results from PTF

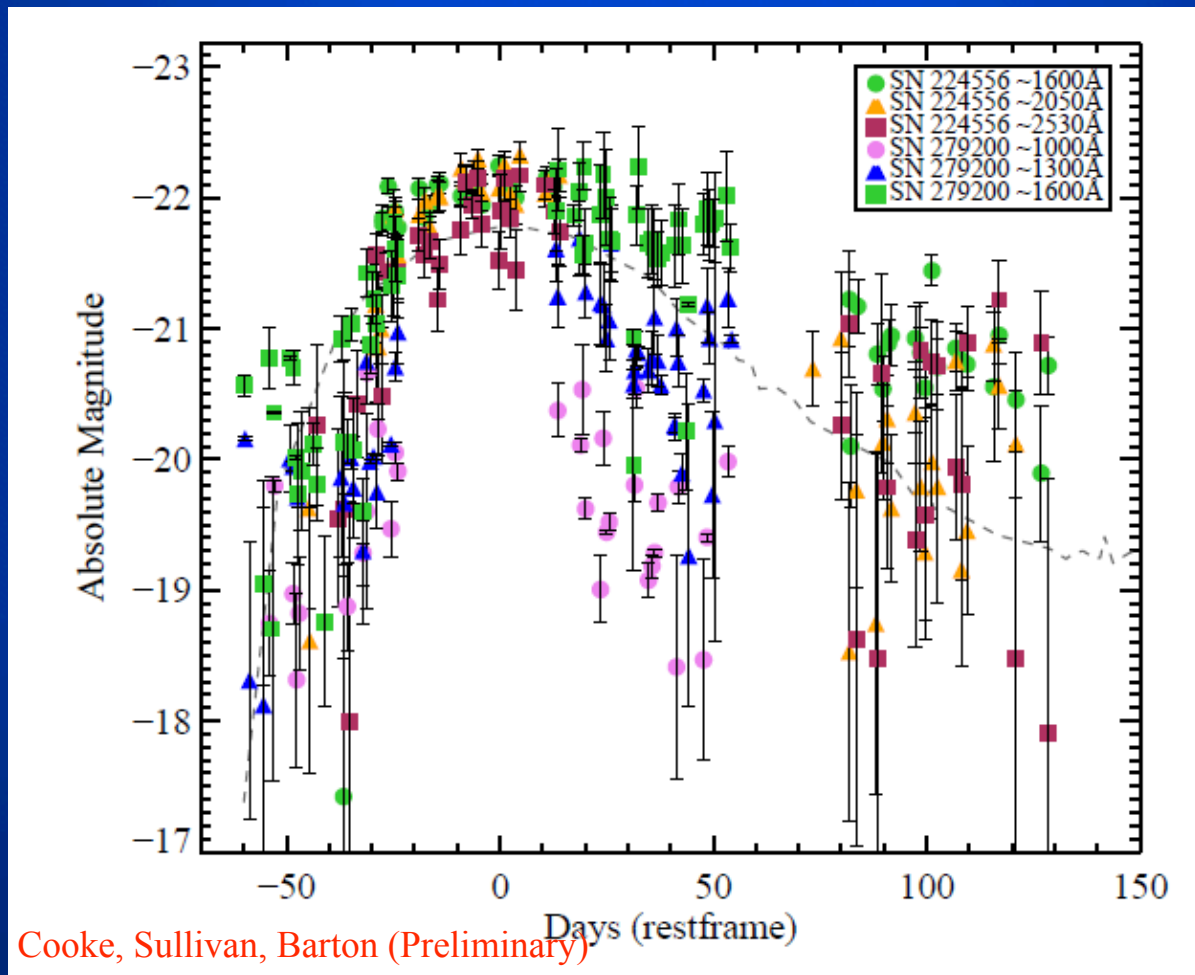
(Yaron)

- Rate at low- $z$  is about  $\sim 1$  per year, these are  $\sim 5$  times rarer than Quimbies (roughly): truly at top of the IMF

# PISNe at high redshift

(Cooke)

- PISNe are also detected at high redshifts (Cooke; PS1)



# PISNe at high redshift

(Cooke)

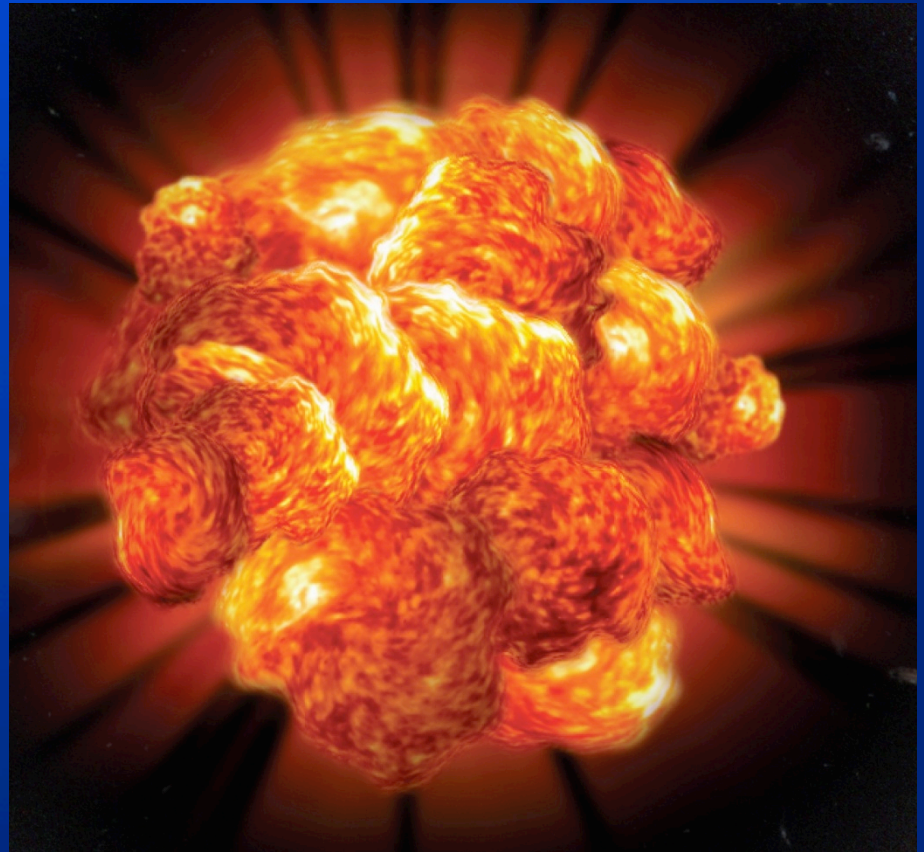
- PISNe are also detected at high redshifts
- They are also rare there
- At the top of the IMF also at high- $z$



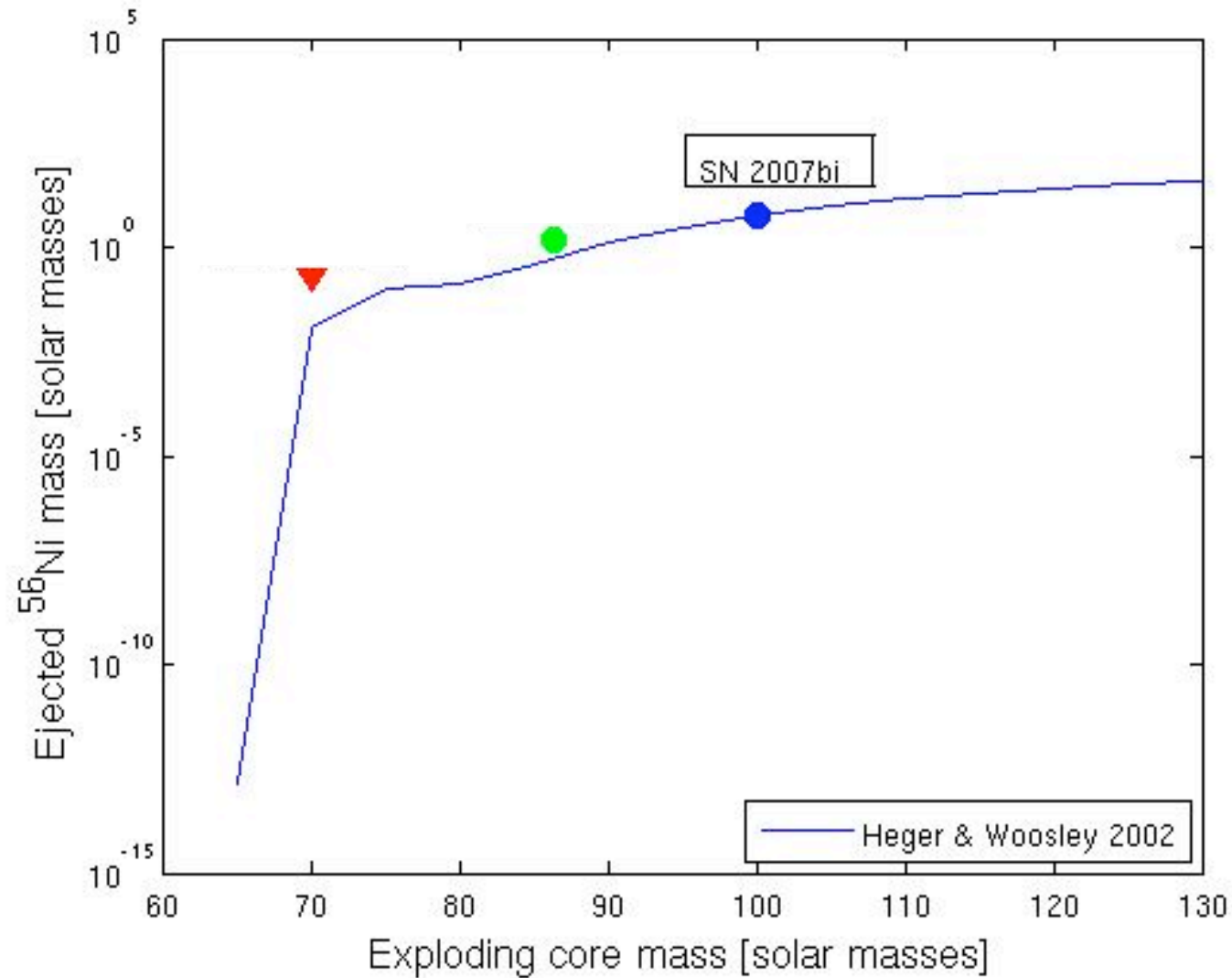
# Implications

(Gal-Yam et al. 2009)

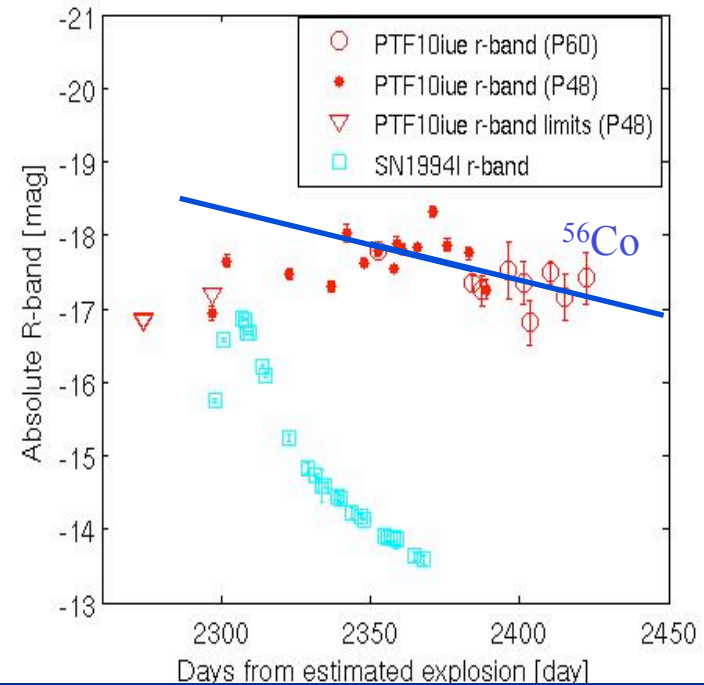
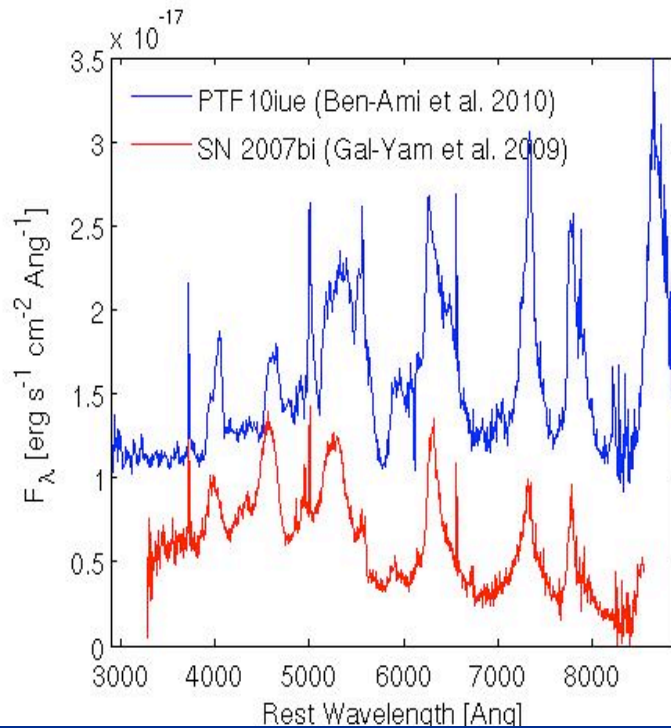
- \* A helium core  $\sim 100$  solar detected at  $Z \sim \text{SMC}$
- Many mass loss models are wrong (c.f Langer models)
- \* PISNe happen locally, Universally, SN models are  $\sim \text{ok}$
- \* Dwarfs have stars above Galactic limit ( $>200$  solar, probably)
- \* Hydrogen efficiently removed (pulsations?)



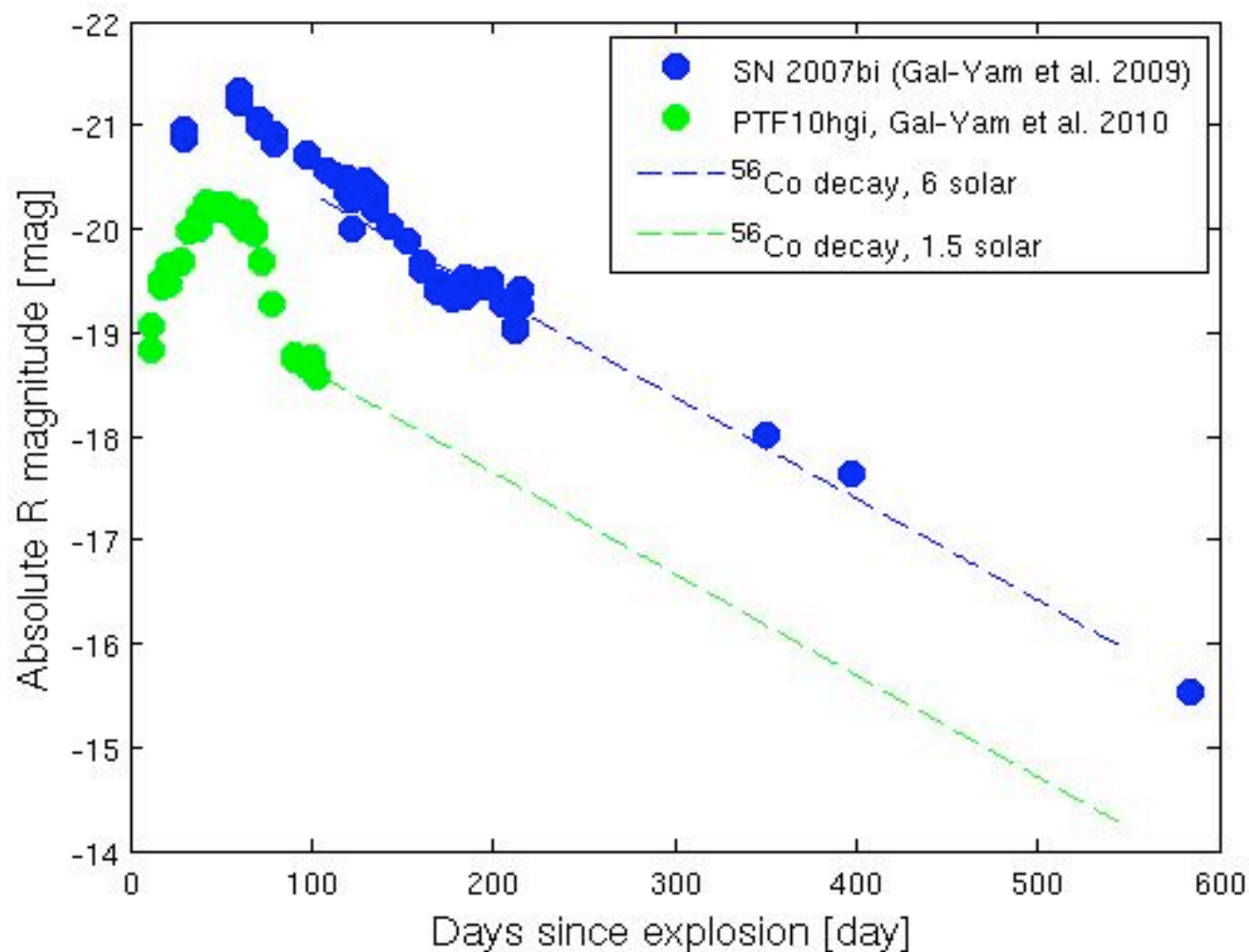
# Implications (observational)



# The new plateau (Ben-Ami)

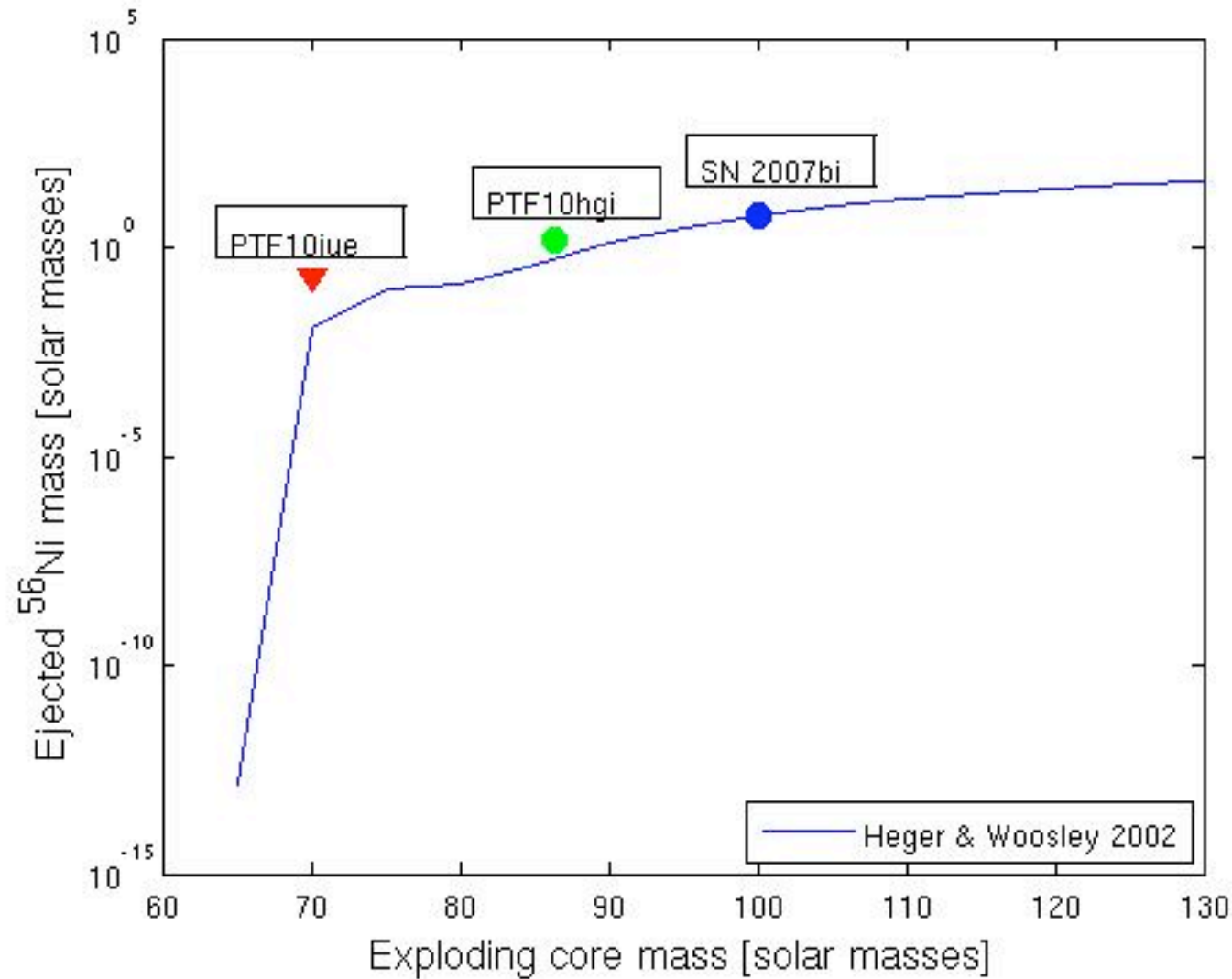


# In the middle

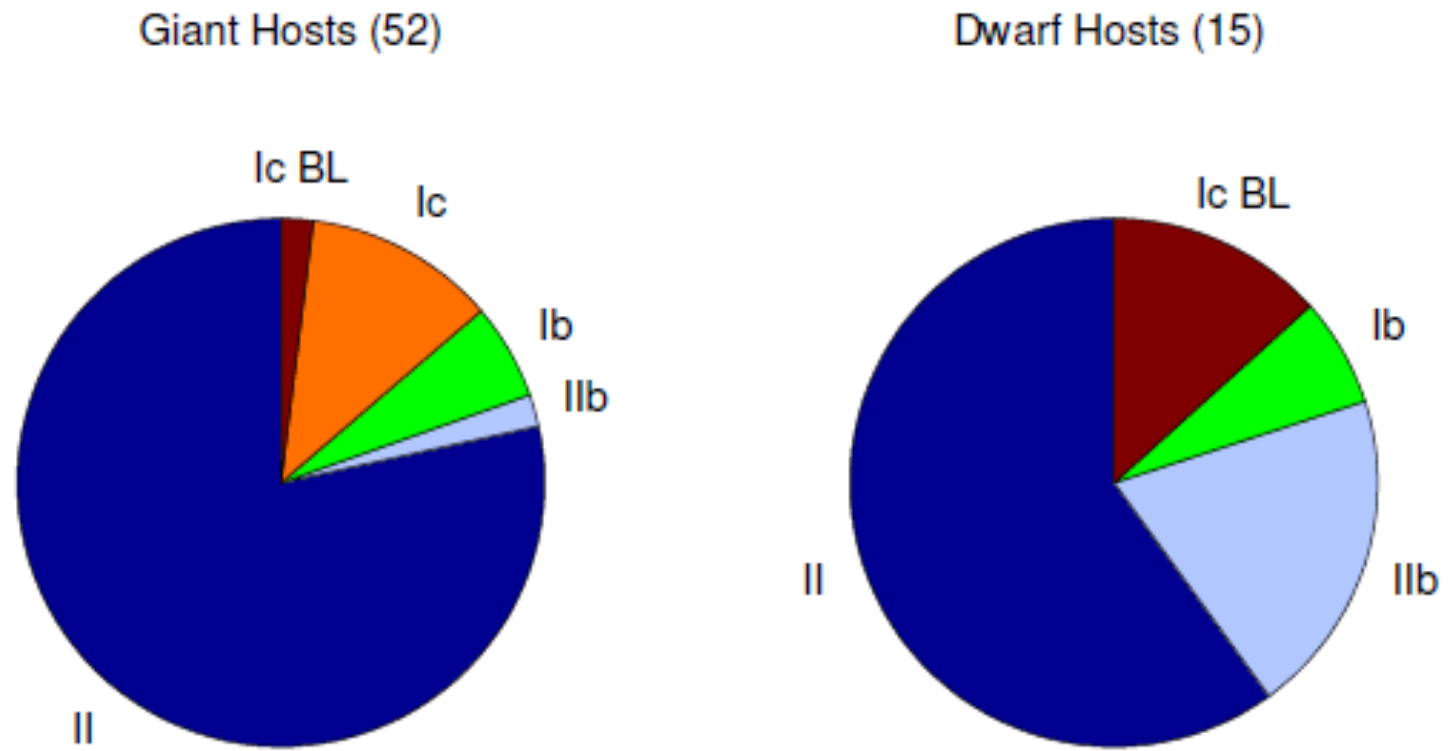




# Implications (observational)



# Dwarf and giant galaxies: different populations of massive star explosions (Arcavi et al. 2010)



# And now... something else

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Zoom Full Auto Zoom Binning= 3

Contrib: Gal-yam et al. 09  
Publish: 2009Natur.462..624G

127 sn2007bi (sn2007bi) PISN PTFdyrun Keck1 - LRIS 2007-04-16 Filippenko+Foley + Silverman+Chornock + Perley+Bloom+Kocevski 2009-07-06 Ryan Chornock 600 1.5 Y sn2007bi-20070416.368-br-scaled+error.flm admin 2011-07-25 admin

Rest (z=0.1279) Wavelength (Å) 3546 4433 5320 6206 7093 7979

2.00 1.75 1.50 1.25 1.00 0.75 0.50

Observed Wavelength (Å) 4000 5000 6000 7000 8000 9000

Zoom Full Auto Zoom Binning= 1

☐ Show H at Z= 0.1279 vexp= 0 km/s  
☐ Show He at Z= 0.1279 vexp= 0 km/s  
☐ Show He II at Z= 0.1279 vexp= 0 km/s  
☐ Show O at Z= 0.1279 vexp= 7000 km/s  
☐ Show O II at Z= 0.1279 vexp= 0 km/s  
☐ Show O III at Z= 0.1279 vexp= 0 km/s  
☐ Show A at Z= 0.1279 vexp= 0 km/s  
☐ Show Na at Z= 0.1279 vexp= 12000 km/s  
☐ Show Mg at Z= 0.1279 vexp= 0 km/s  
☐ Show Mg II at Z= 0.1279 vexp= 0 km/s  
☐ Show Si II at Z= 0.1279 vexp= 0 km/s  
☒ Show Ca II at Z= 0.1279 vexp= 0 km/s  
☐ Show Fe II at Z= 0.1279 vexp= 0 km/s  
☐ Show Tellurics

Contrib: Gal-yam et al. 09  
Publish: 2009Natur.462..624G

For comments/questions, please contact wisepass.db@gmail.com.

Done

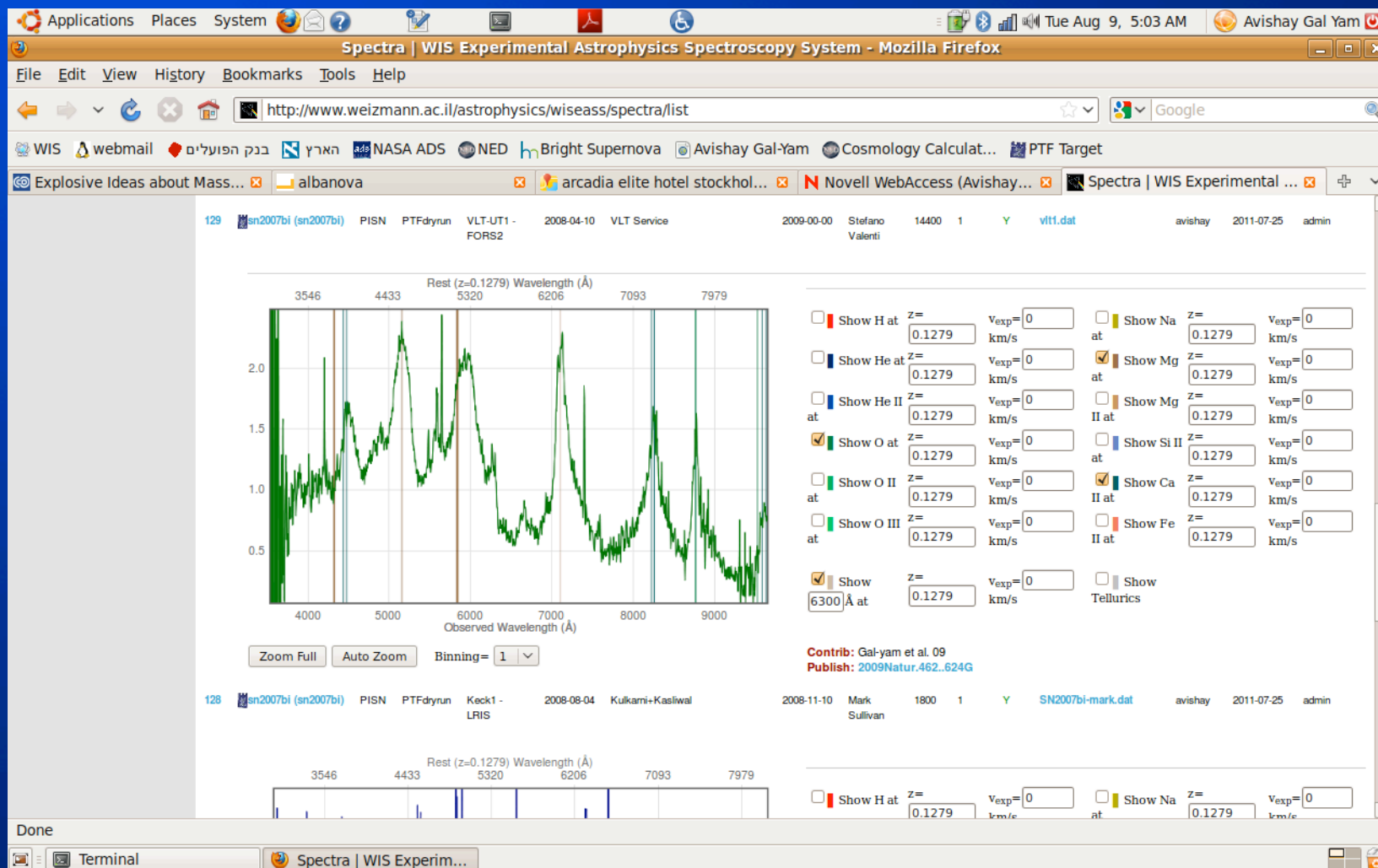
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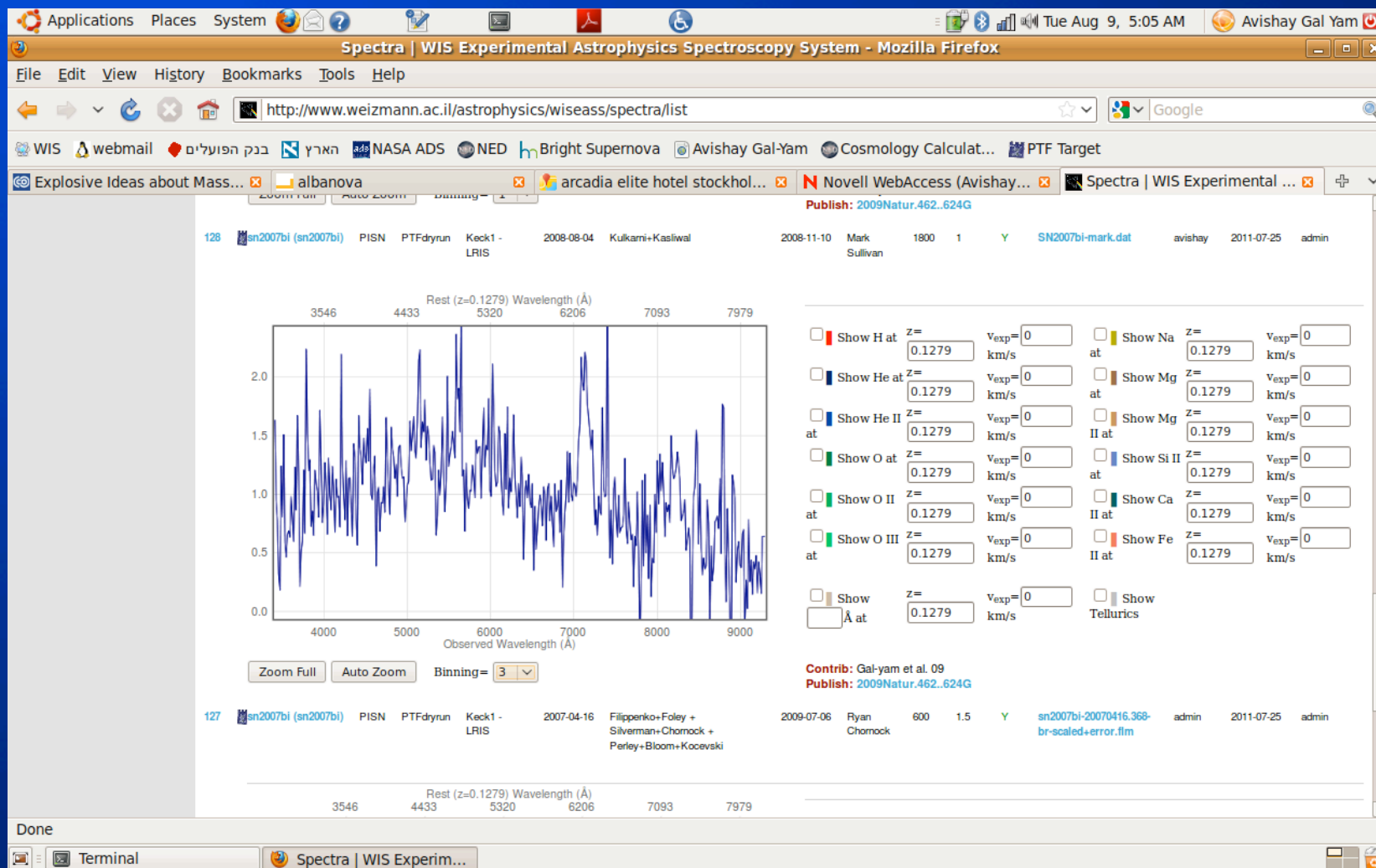




# The Weizmann Institute of Science Experimental Astrophysics Spectroscopy System (WISEASS)



# The Weizmann Institute of Science Experimental Astrophysics Spectroscopy System (WISEASS)



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Explosive Ideas about Mass... albanova arcadia elite hotel stockhol... Novell WebAccess (Avishay... Spectra | WIS Experimental ...

7 row(s) returned.

ID	Obj. Name	Type	Program	Instrument	Obs. Date	Observer	Red. Date	Reducer	Exp	Slit	Public	Ascii	Created By	Last Modified	Modified By
2554	ptf11eon (sn2011dh)	SN Iib	PTF	P200 - DBSP	2011-08-06	Assaf Horesh, Yi Cao	2011-08-07	Dong Xu	120	1.5	N	PTF11eon- 20110806.dat	dong-BunchUpload	2011-08-08	dong-BunchUpload

Rest (z=0.001638) Wavelength (Å)

Observed Wavelength (Å)

Zoom Full Auto Zoom Binning= 1

703 ptf11eon (sn2011dh) SN Iib PTF P200 - DBSP 2011-06-28 Sagi Ben-ami 2011-06-30 Polishock+Stenberg 150 1 N PTF11eon-20110628.flm david-BunchUpload 2011-07-03 david-BunchUpload

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- CCCP
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- SUSPECT SN Archive
- Spectrophotometric Standards

☒ Show H at  $z=0.001638$   $v_{exp}=11000$  km/s  
☒ Show He at  $z=0.001638$   $v_{exp}=6000$  km/s  
☐ Show He II at  $z=0.001638$   $v_{exp}=0$  km/s  
☐ Show O at  $z=0.001638$   $v_{exp}=0$  km/s  
☐ Show O II at  $z=0.001638$   $v_{exp}=0$  km/s  
☐ Show O III at  $z=0.001638$   $v_{exp}=0$  km/s  
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☐ Show Tellurics

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- No. of Spectra 2486
- No. of Objects 1616
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3 row(s) returned.

ID	Obj. Name	Type	Program	Instrument	Obs. Date	Observer	Red. Date	Reducer	Exp	Slit	Public	Ascii	Created By	Last Modified	Modified By
55	sn2005cl (sn2005cl)	SN IIn	CCCP	P200 - DBSP	2005-09-08	Brad Cerko	2008-01-01	Michael Kiewe	1800	1	Y	sn2005cl-20050908-br.flm	avishay	2010-12-15	avishay

Rest (z=0.025878) Wavelength (Å)

Observed Wavelength (Å)

Zoom Full Auto Zoom Binning= 1

☒ Show H at  $z=0.025878$   $v_{exp}=900$  km/s  
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☐ Show He II at  $z=0.025878$   $v_{exp}=0$  km/s  
☐ Show O at  $z=0.025878$   $v_{exp}=0$  km/s  
☐ Show O II at  $z=0.025878$   $v_{exp}=0$  km/s  
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☐ Show Si II at  $z=0.025878$   $v_{exp}=0$  km/s  
☒ Show Ca II at  $z=0.025878$   $v_{exp}=900$  km/s  
☒ Show Fe II at  $z=0.025878$   $v_{exp}=900$  km/s  
☐ Show Tellurics at  $z=0.025878$   $v_{exp}=0$  km/s

Remarks: Reduced by Michael Kiewe during 2008; published in Kiewe 2009 (M.Sc thesis) and Kiewe et al. 2010 (<http://adsabs.harvard.edu/abs/2010arXiv1010.2689K>)

Publish: 2010arXiv1010.2689K

52 sn2005cl (sn2005cl) SN IIn CCCP P200 - DBSP 2005-08-13 Brad Cerko 2008-01-01 Michael 1800 1.5 Y sn2005cl-20050813- avishay 2010-12-15 avishay

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