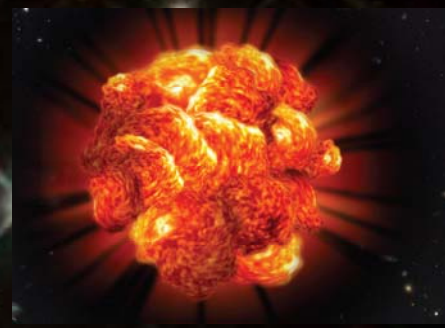
A Variety of Stellar Deaths:

Connecting massive stars to a range of outcomes



Avishay Gal-Yam,

Benoziyo Center for Astrophysics

Weizmann Institute

Bobfest 2009, KITP

The Core-Collapse Spectrum

Lower mass limit unclear:

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

Electron Capture

Metallicity

Binarity

Rotation …

# of Events

7-11

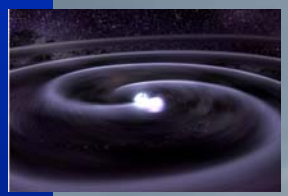
Initial mass

The Core-Collapse Spectrum

Lower mass limit unclear:

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

EC SN?



Accretion-induced collapse

M: 7-11

Accretion induced collapse (AIC)

EC explosion in an old ONeMg WD following accretion (Nomoto 1984)

Possible explanation for new class of SNe: Ca-rich faint SNe Ib, provided donor is a He WD

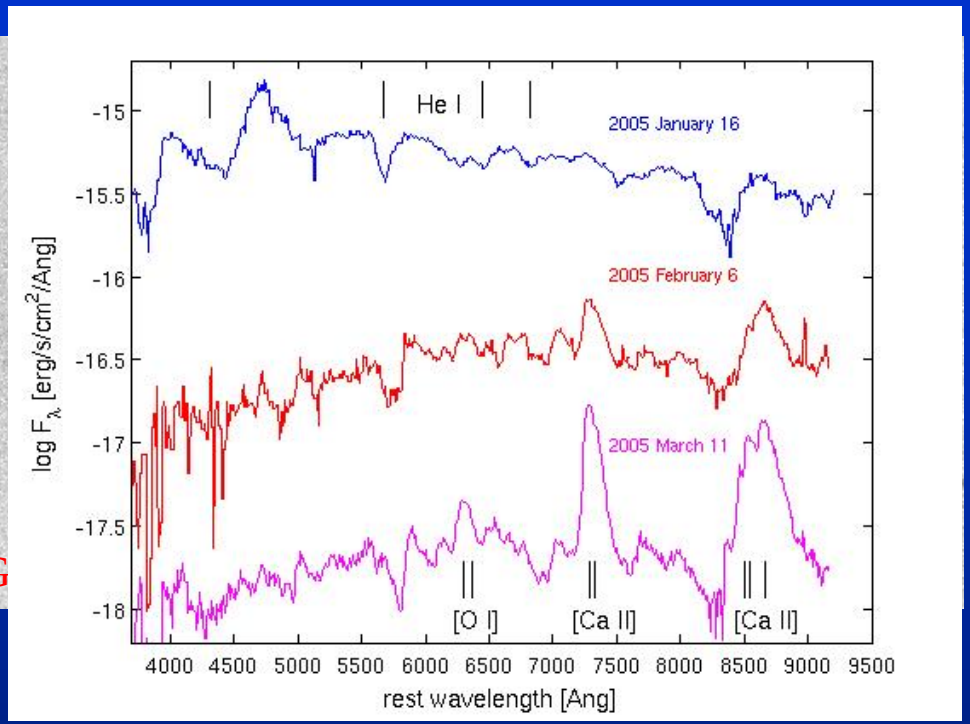
The Story of SN 2005E

LOSS discovery

Type Ib (UCB; CCCP)

Member of the Ca-rich

Subclass (Filippenko et al.)



Hagai Perets

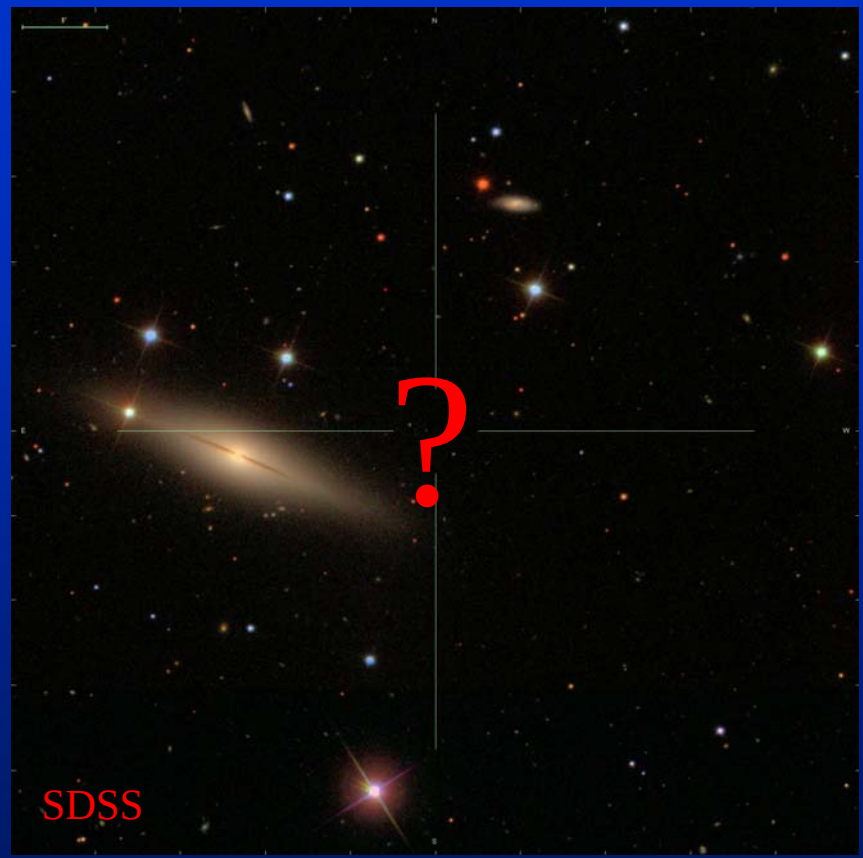
Dave Arnett, Paolo Mazzali, Daniel Kagan, UCB SN group, CCCP, Anderson & James, Ofek, Bildsten & Co., Quataert & Co.

The Story of SN 2005E (Cont.)

CCCP2 follow-up shows … nothing

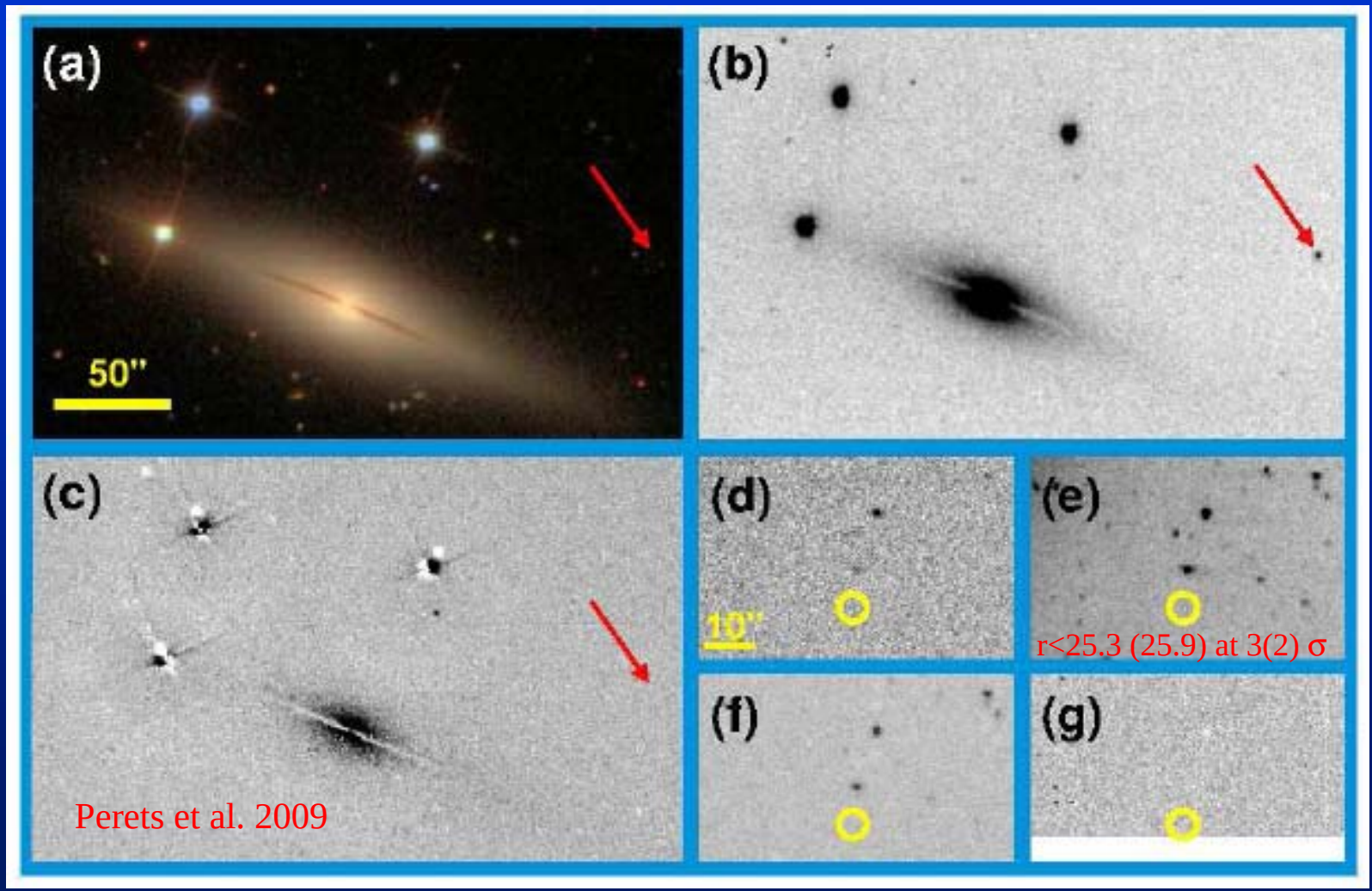
SN 2005E exploded in a remote location, at the outskirts of an isolated, regular, edge-on S0/a galaxy

A type Ib? How did the massive progenitor get there?



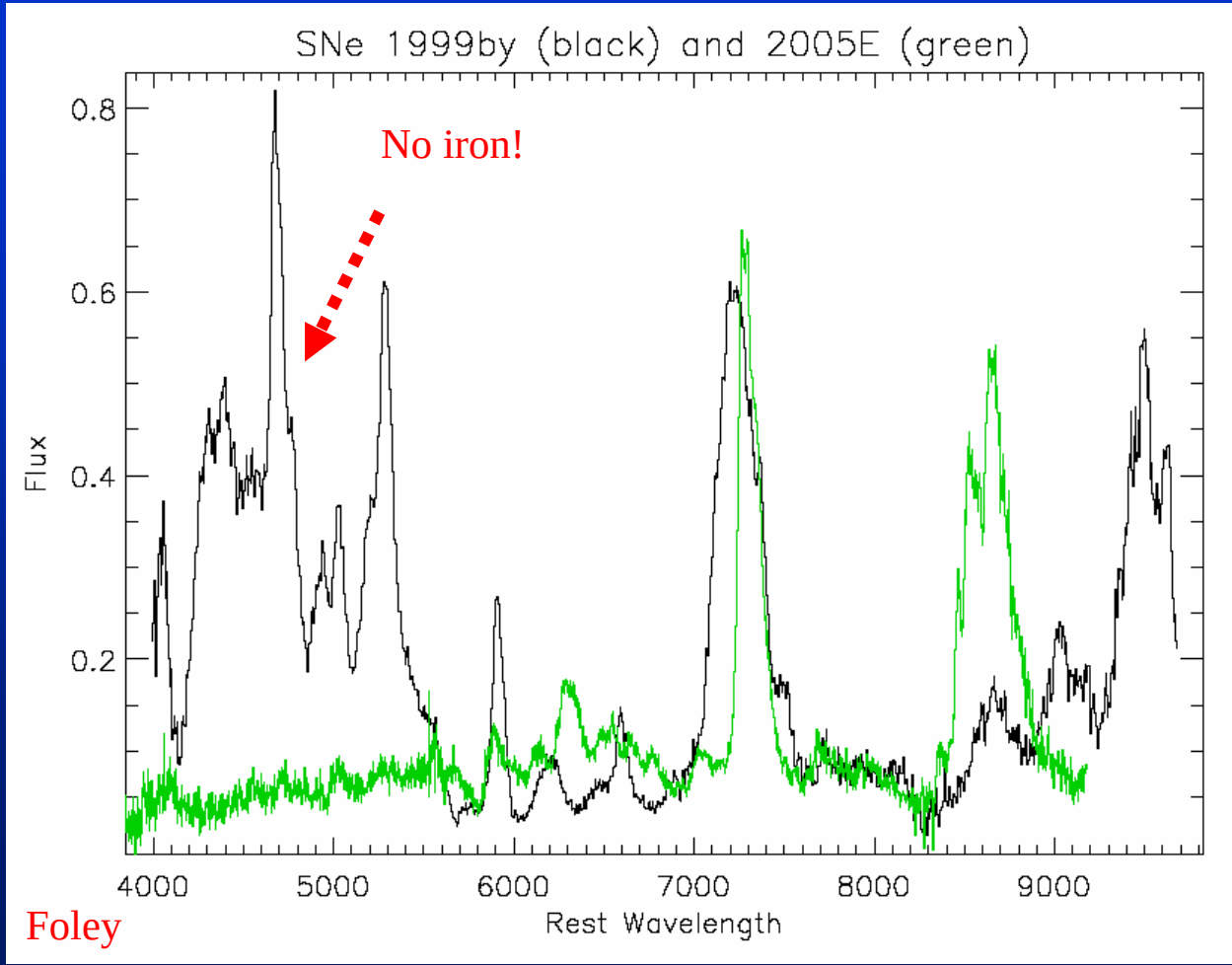
Local star formation?

Not detected to deep limits … unlikely also on theoretical grounds



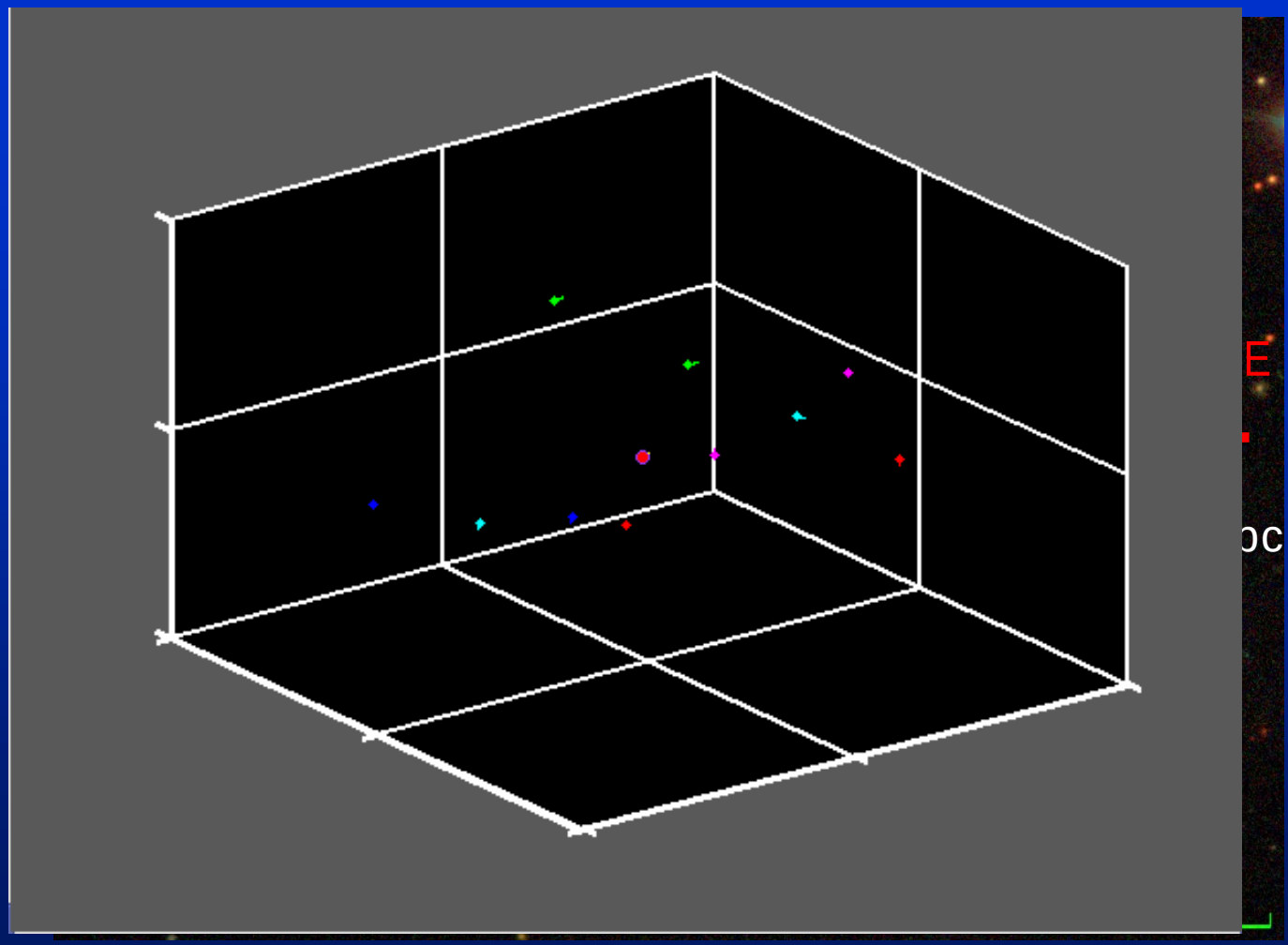
A weird type Ia?

Spectra conclusively rule out SN Ia identification



A hyper-velocity SN (HVSN) ?

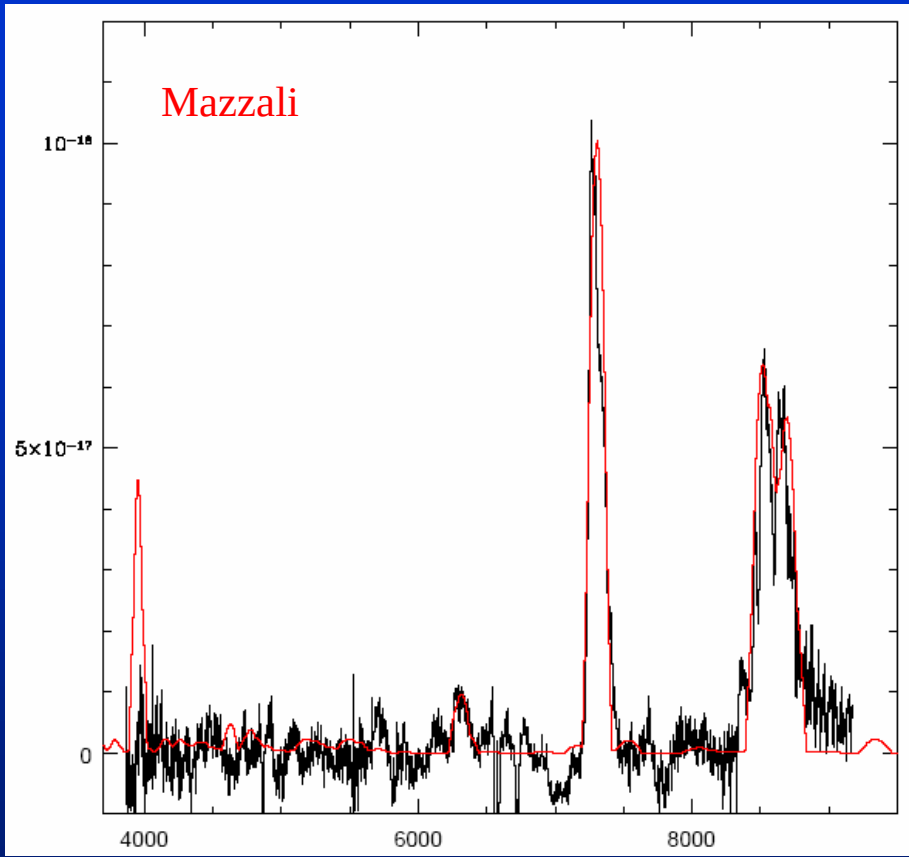
Life in the fast lane?



Not likely: chances to observe HVSNe with LOSS are < 1/100

So what, then?

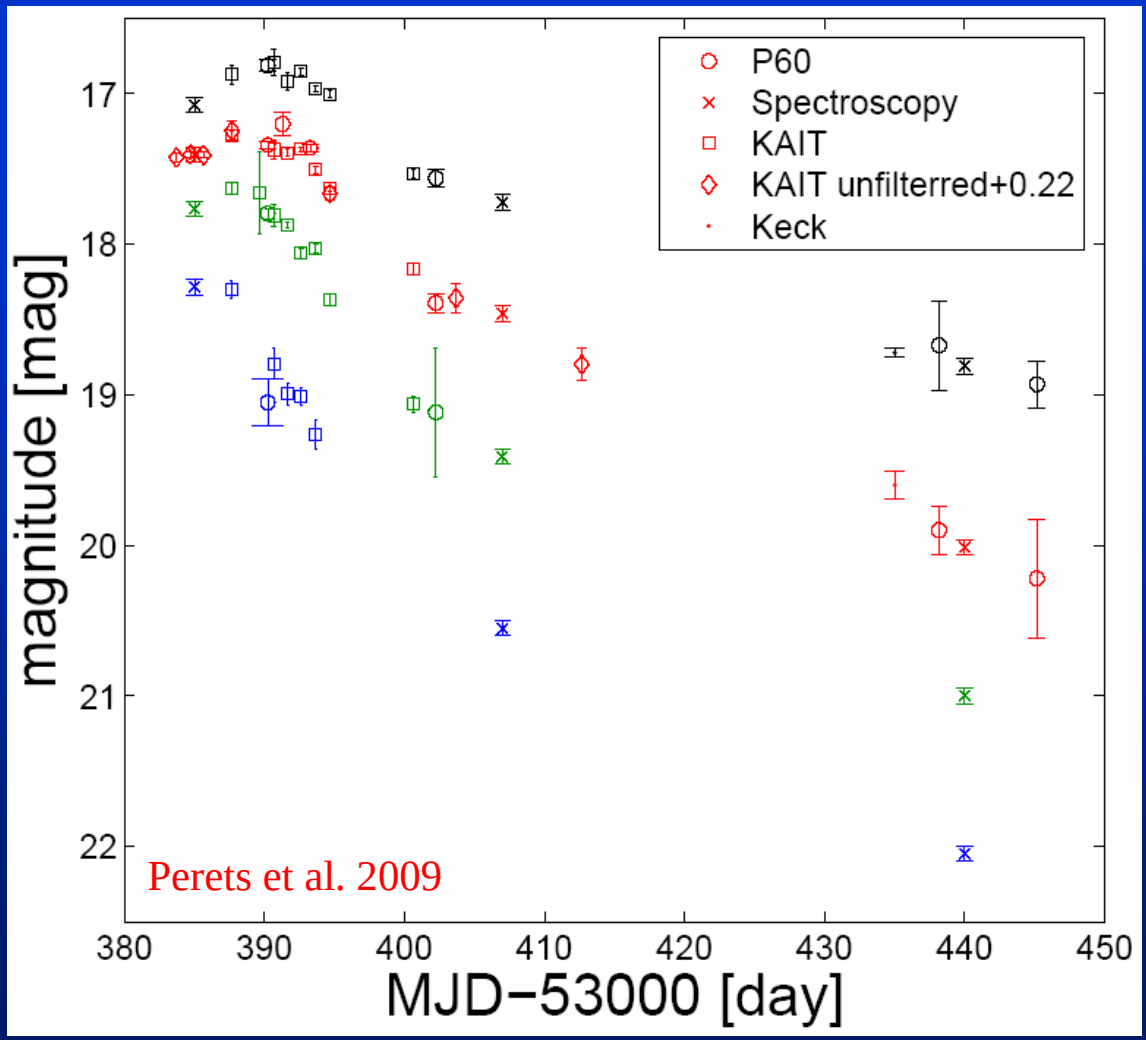
What will nebular spectra reveal?



Peculiar abundances (C, Ca, O, Ni56) = (0.12 0.06 0.02 0.003) solar

Total ejected mass is ~0.2 solar !

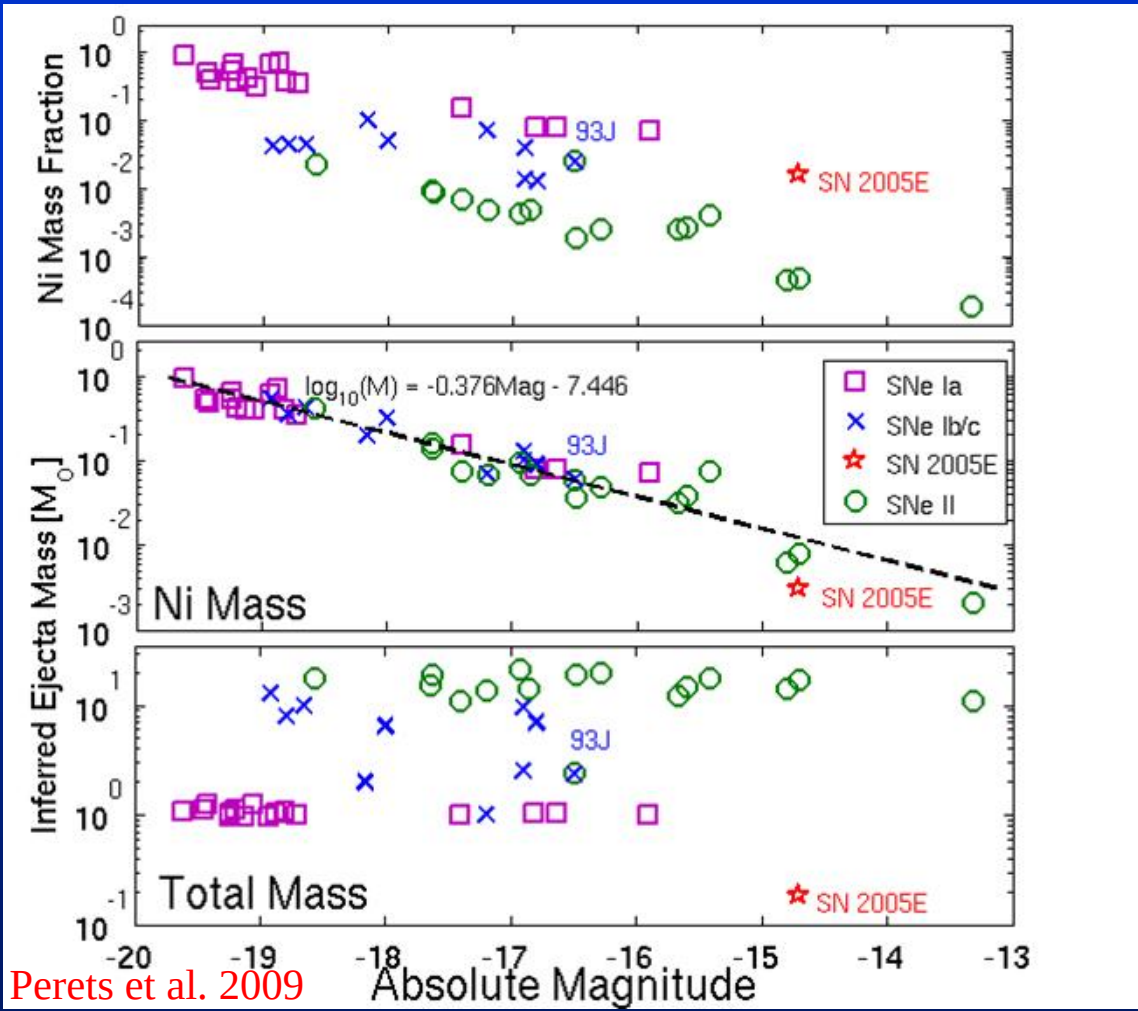
Mass estimate confirmed by light curve analysis



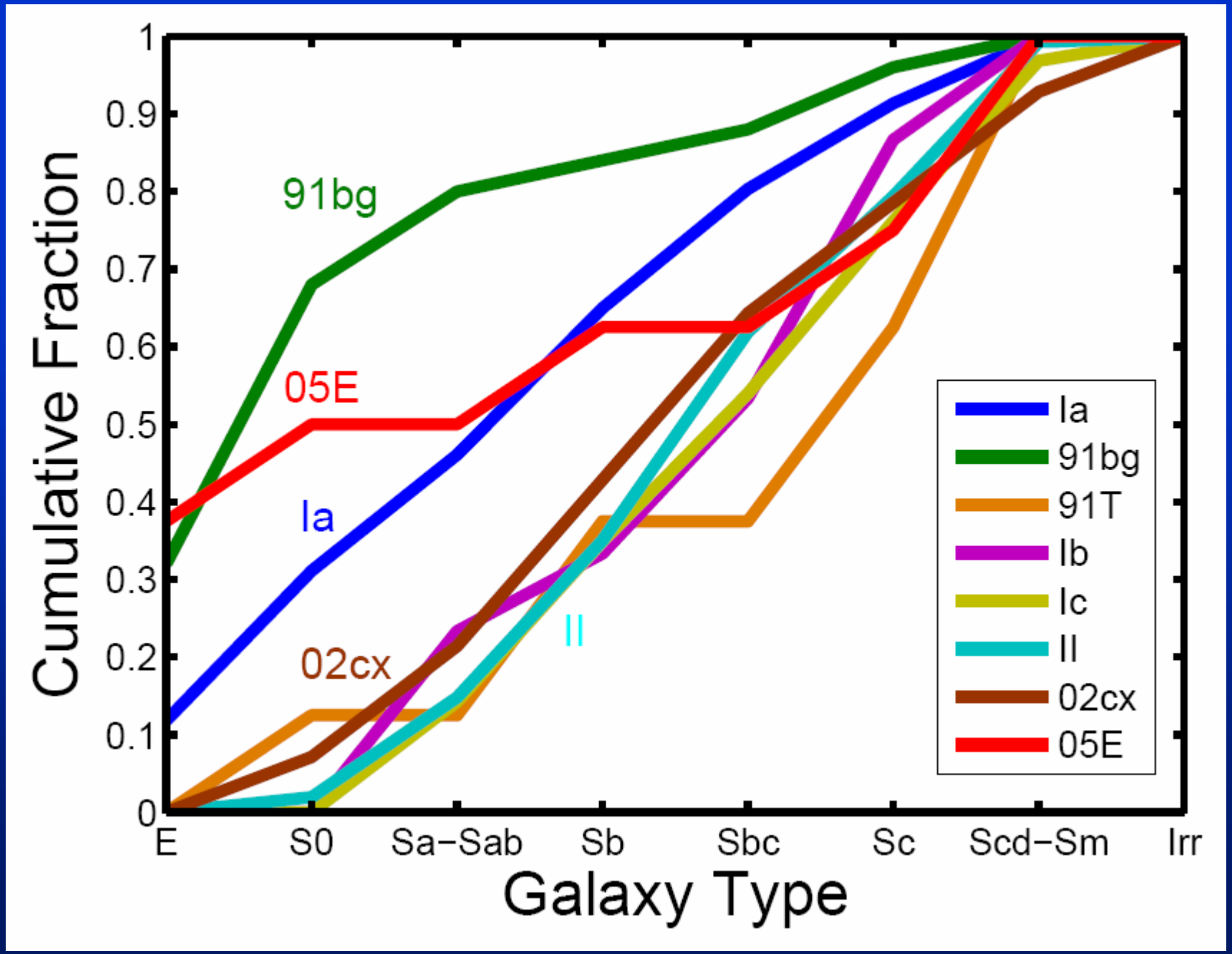
M ~ 0.3 solar

A new type of supernova

Not a core collapse, nor SN Ia



Perets et al. 2009


Cumulative Fraction
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
E
S0
Sa−Sab
Sb
Sbc
Sc
Scd−Sm
Irr
Galaxy Type
91bg
05E
Ia
02cx
II
Ia
91bg
91T
Ib
Ic
II
02cx
05E

What can it be?

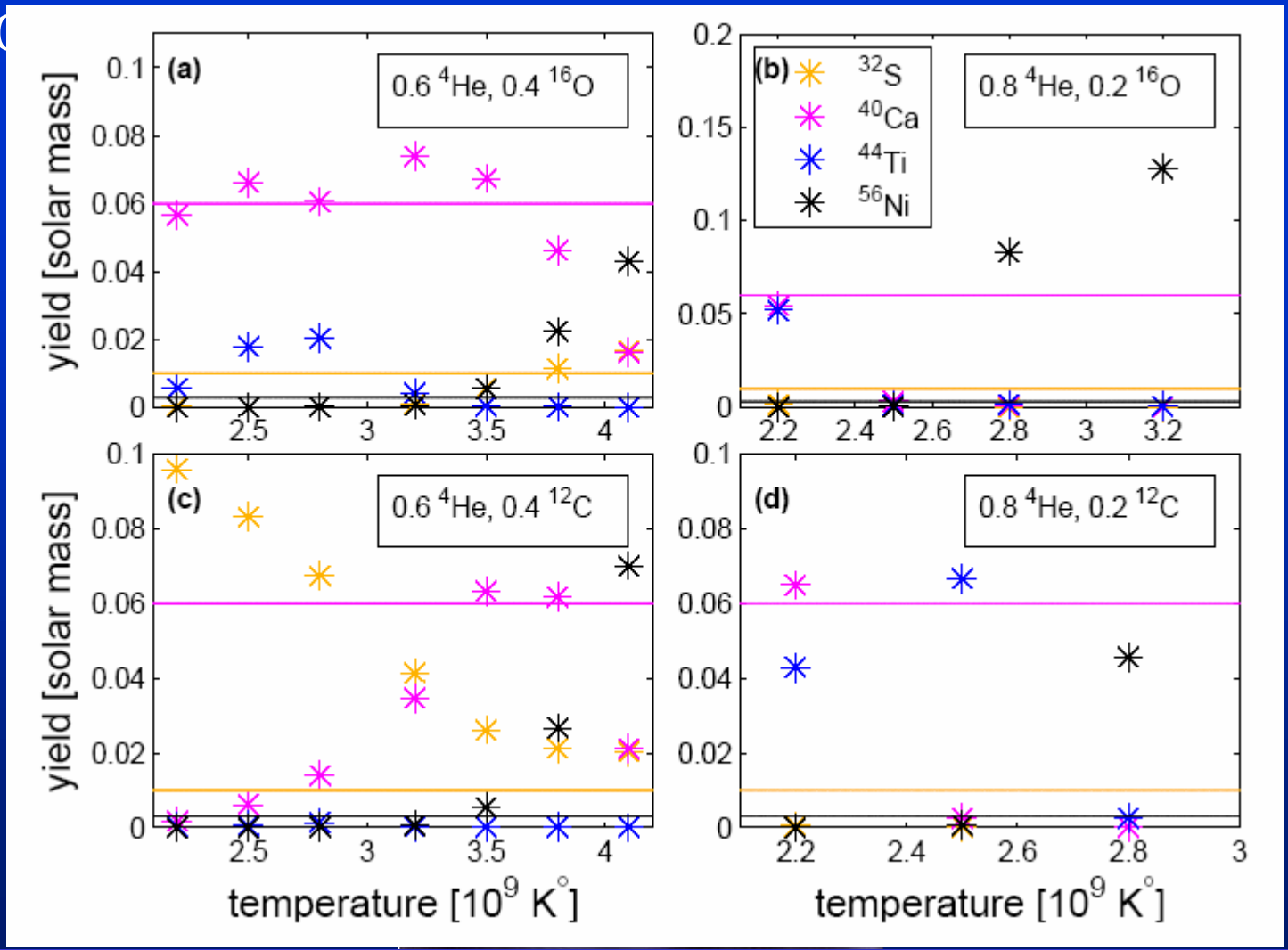
Possibilities reviewed by Foley, Valenti (for SN 2008ha):

~~* Core collapse to a black hole ("failed SN")~~ ◀▪▪ No SFR, hosts

~~* Weak/partial deflagration~~ ◀▪▪ High velocities, nucleosynthesis

* AIC
* ".Ia" } ◀▪▪ He accretion in a DD system

Nucleosynthesis



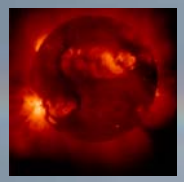
He/C/O accretion/merger result an emerging field

The Core-Collapse Spectrum

Lower mass limit unclear:

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

EC SN?

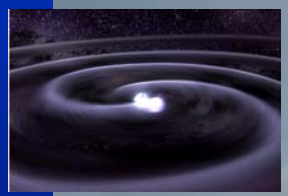


RSG=II-P

Smartt

?

"The gap"



AIC

M: 7-11 M: 8-16 M: 17-25

The Core-Collapse Spectrum

Lower mass limit unclear:

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

The Core-Collapse Spectrum

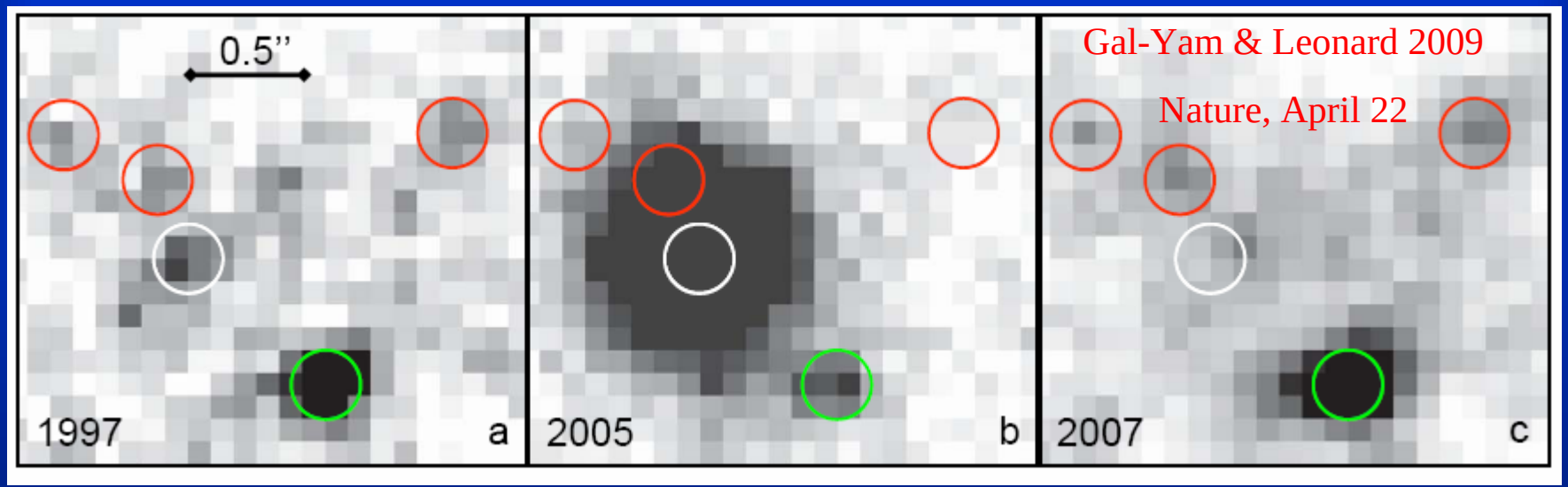
Lower mass limit unclear:

<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

SNe IIn from very massive stars (LBVs)

* Direct detection of the progenitor of SN 2005gl: L~10^6 solar



* In accord with works by Kotak, Smith, Trundle, …

* May involve the pulsational pair instability (PPSN; Woosley et al. 2007; Smith et al. 2009; Miller et al. 2009)

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

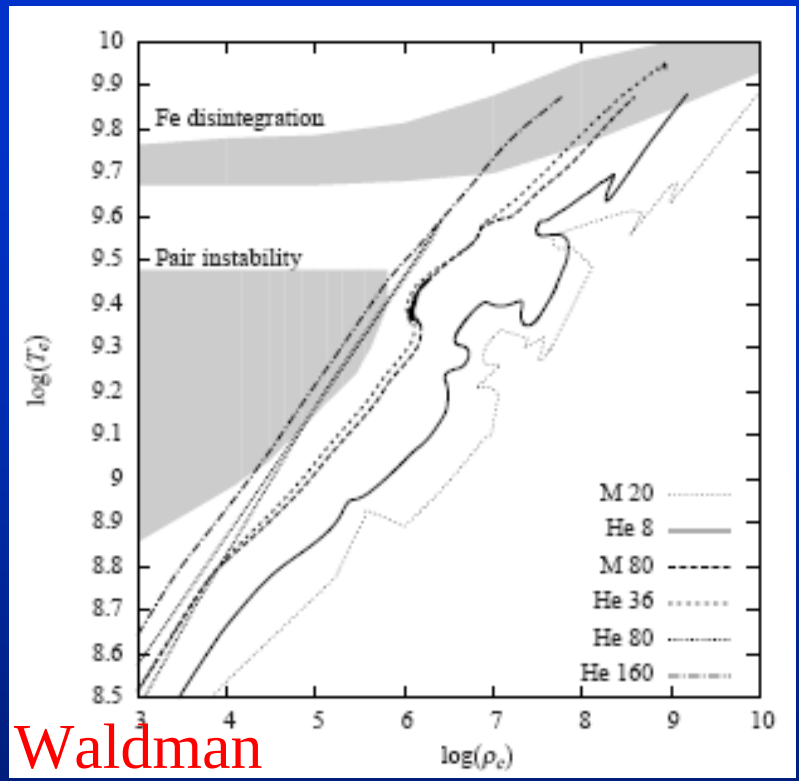
Pair Instability Supernovae (PISNE)

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

* Helium cores above ~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



Waldman

* "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)

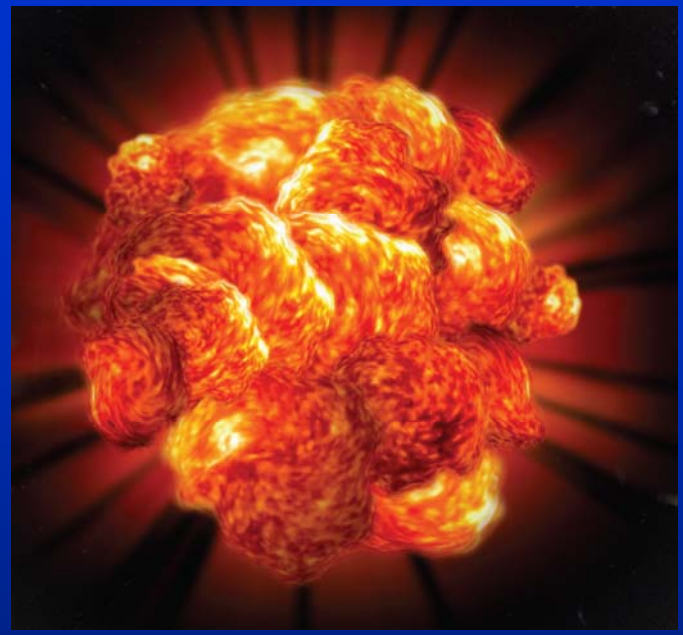
(Barkat, Rakavi & Sack 1967 ; Heger & Woosley 2002; Waldman 2008 …)

* 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~1000 stars may have existed



SN 2007bi=SNF20070406-008

(PTF "dry run")

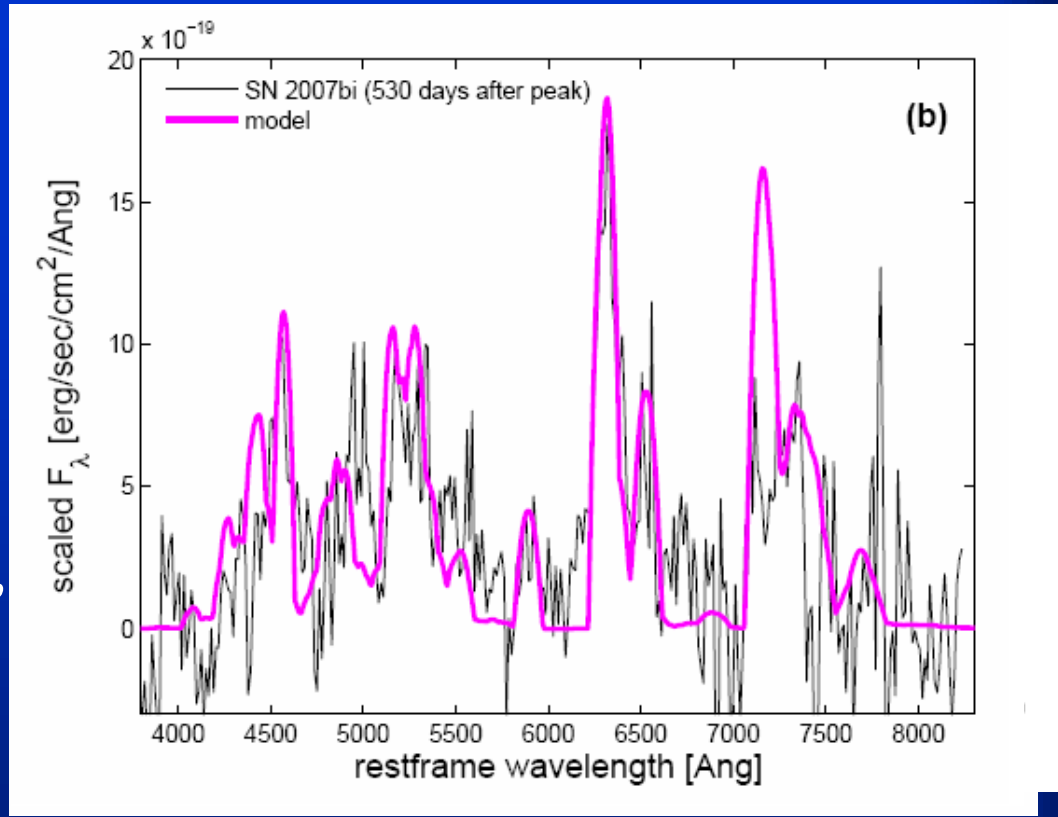
* Type Ic SN similar to SN1999as. No interaction, no dust, v=12000 km/s

* Luminous peak (-21.3), slow rise (~77 days), ^{56}Co decay

* M>3 solar masses of ^{56}Ni, ejected mass ~100 solar, E_k~1e53 (scaling), 4-11 solar masses of ^{56}Ni (87A)

* Well-fit by models (Kasen)

* Nebular spectra: 4-6 solar mass of ^{56}Ni; >50 solar total (Mazzali), consistent with 98bw



Core mass > 50 robustly established;

Gal-Yam et al. 2009, also Young et al. 2009

Implications

(Gal-Yam et al. 2009)

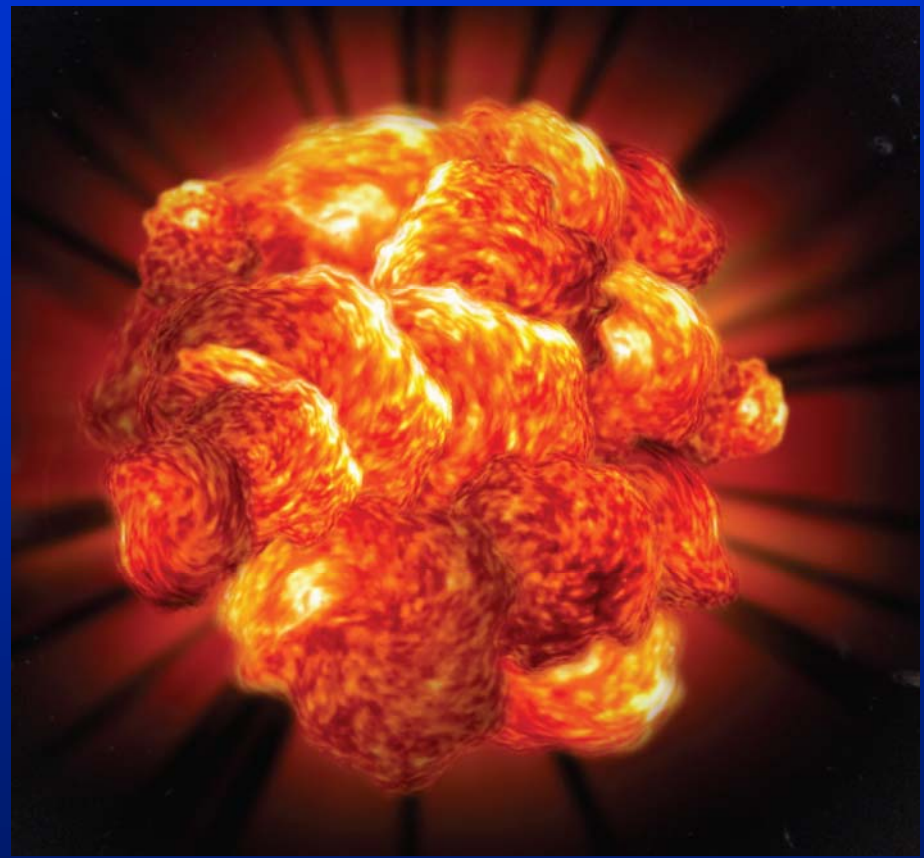
* A helium core ~100 solar detected at Z ~ SMC

* Mass loss models are wrong

* PISNe happen locally, Universally, models are ~ok

* Dwarfs have stars above Galactic limit (>200 solar, probably)

* Hydrogen efficiently removed (pulsations?)



Physical parameters:

Quantity	Method	Value [range]	Assumptions
^{56}Ni mass	Peak magnitude	$3.5\,M_\odot$	
	SN 1987A comparison	$5.3\ [4.4\ ..\ 7]\,M_\odot$	$t_{rise} = [45..110]$ days, $BC_R = [-0.75..1]$ mag
	Nebular modelling	$[3.7\ ..\ 7.4]\,M_\odot$	$t_{rise} = [45..110]$ days
	SN 1998bw comparison	$8.9\ [7.7\ ..\ 11.3]\,M_\odot$	$t_{rise} = [45..110]$ days
	Light-curve models	$[2.7\ ..\ 11]\,M_\odot$	ref. 8
Ejected mass	Nebular modelling	$[51\ ..\ 61]\,M_\odot$	$t_{rise} = [45..110]$ days
	Light-curve scaling	$105\ [37\ ..\ 173]\,M_\odot$	$t_{\rm rise} = [45..110]$ days
	Light-curve models	$[95\ ..\ 110]\,M_\odot$	ref. 8
Kinetic energy	Light curve scaling	$132\ [68\ ..\ 273]\ 10^{51}$ erg	$t_{\rm rise} = [45..110]$ days
	$(1/2)M_{\rm ej} \times \bar{v}^2$	$80\ 10^{51}$ erg	$M_{\rm ej} = 100\,M_\odot, \bar{v} = 8,000\,{\rm km\,s^{-1}}$
Radiated energy	Direct integration	$[1\ ..\ 2]\ 10^{51}$ erg	$BC_R = [-0.75..1]$ mag

The Core-Collapse Spectrum

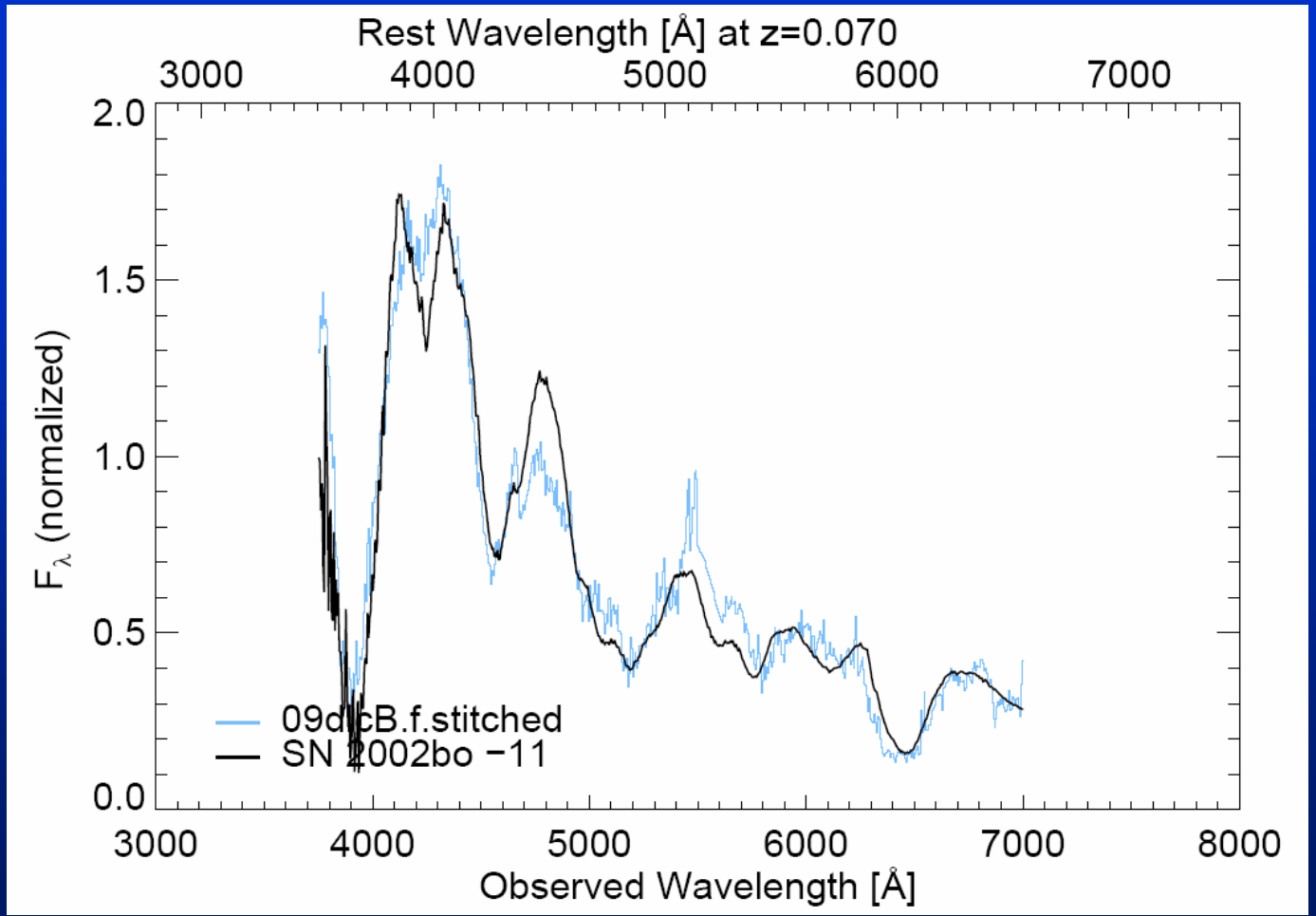
Lower mass limit unclear:

<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

"Spectrum is truth" (RPK)

PTF news … young SNe Ia to HST …



Thanks