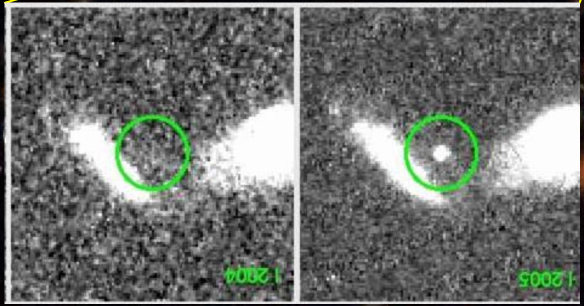
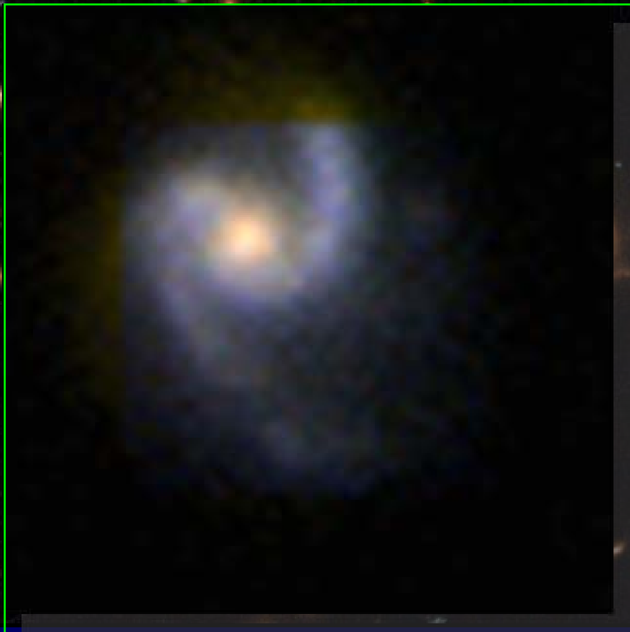
Corfu, 9/2012

Type-Ia Supernovae and the progenitor problem

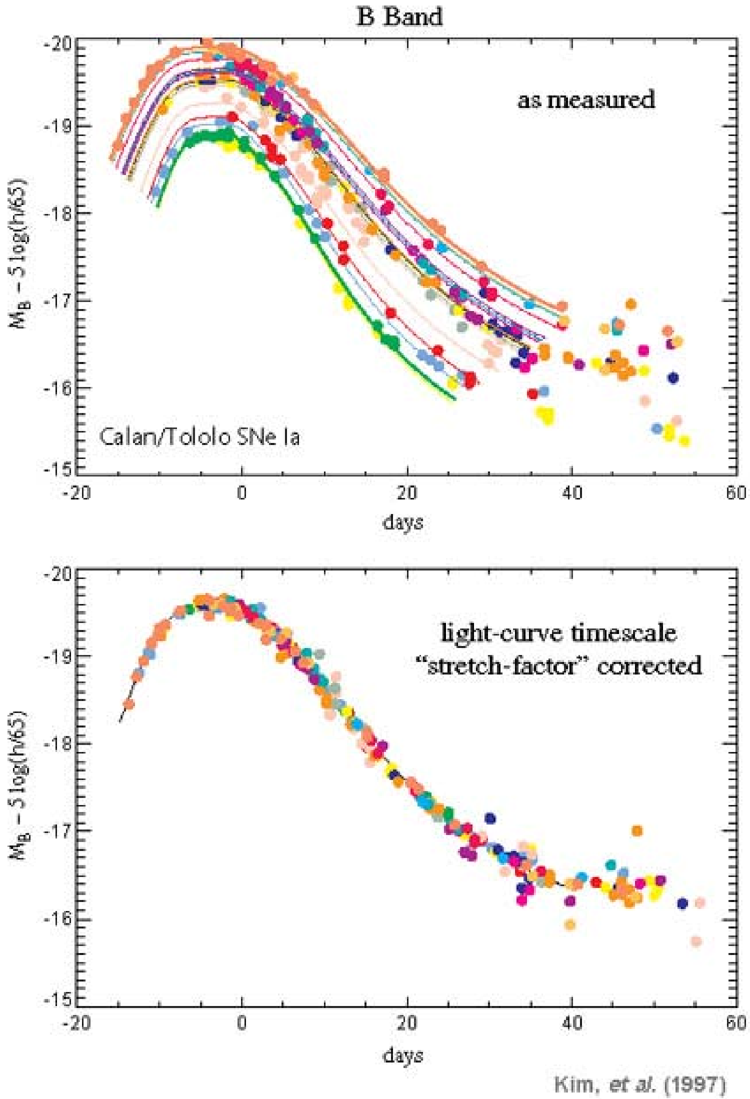
Dan Maoz, Tel-Aviv U.



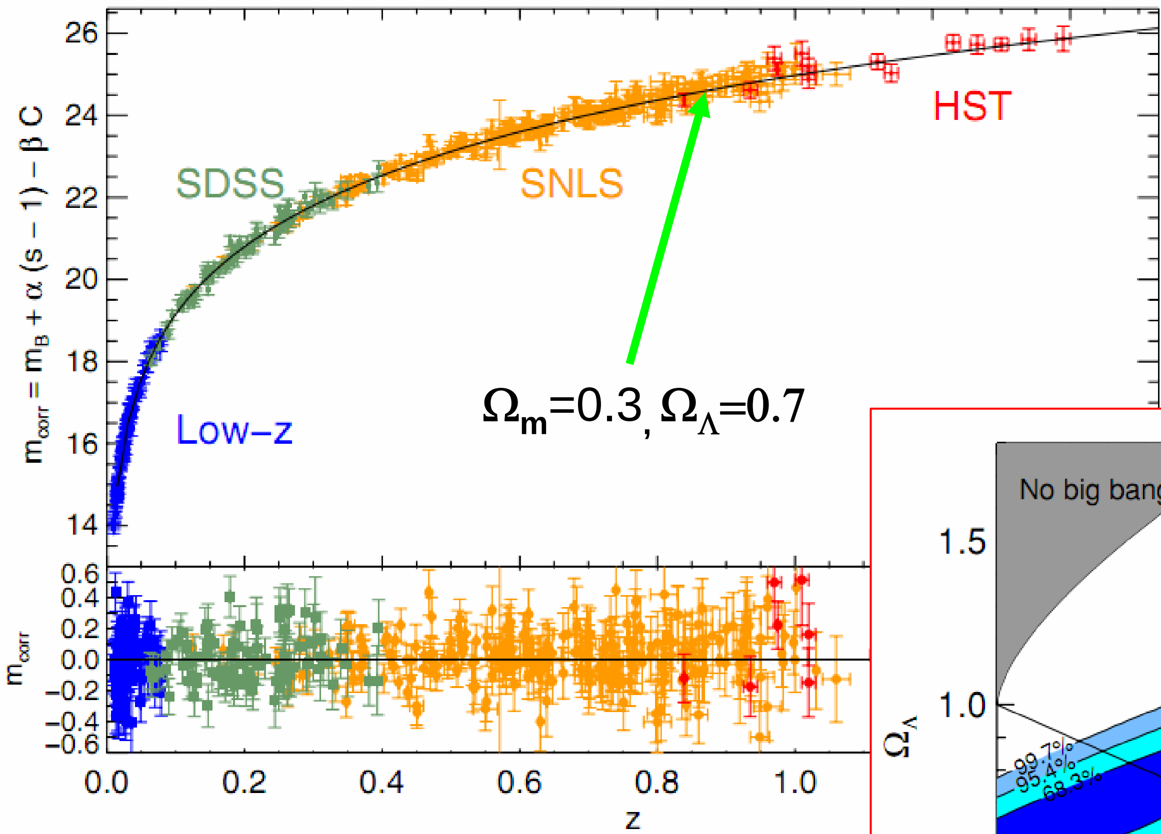


Thermonuclear ("Type-Ia") supernovae are wonderful cosmic distance indicators!

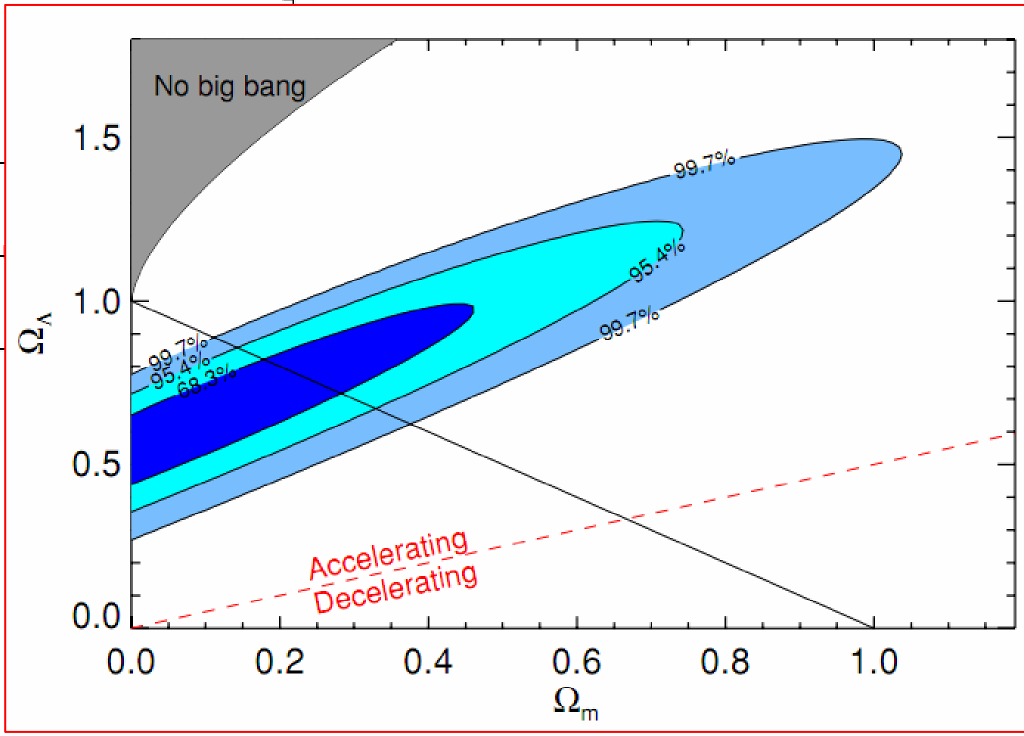
A. Howell, SNLS


B Band
as measured
Calan/Tololo SNe Ia
$M_B - 5\log(h/65)$
days
light-curve timescale
"stretch-factor" corrected
$M_B - 5\log(h/65)$
days
Kim, et al. (1997)

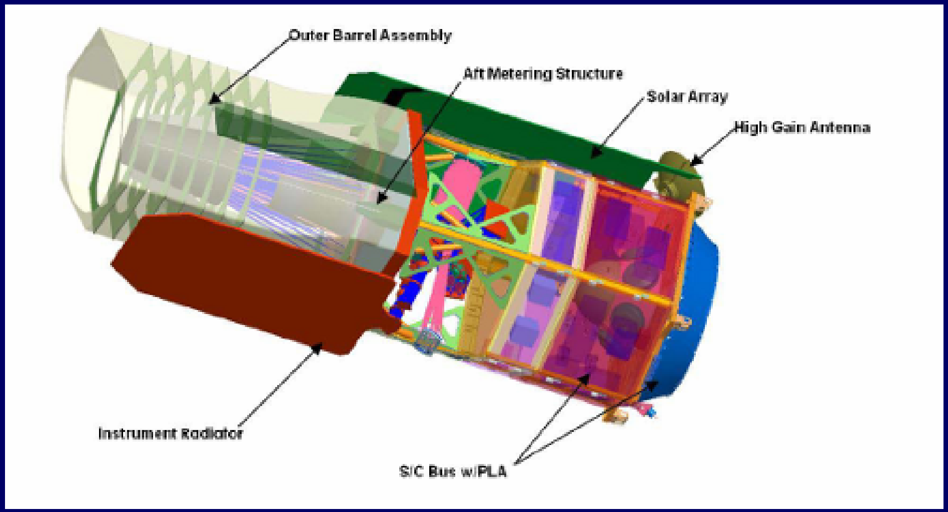
Type-Ia Supernovae, in 1998 – the first heralds of “dark energy”



Conley et al. 2011

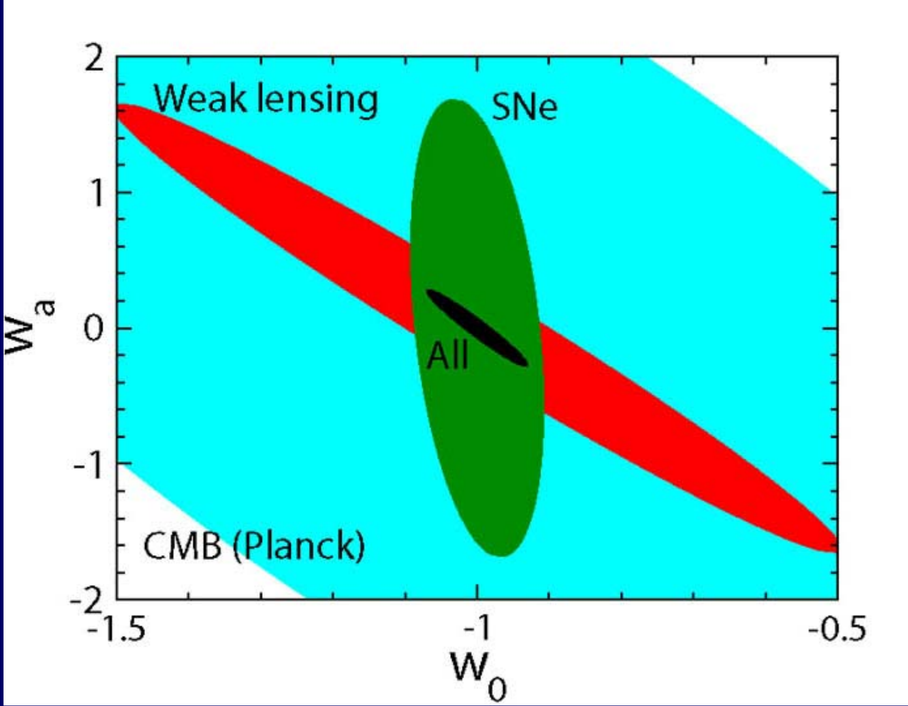


WFIRST (2025?)
1500 SNe Ia



$p/\rho = w(a) = w_0 + w_a(1-a)$,

$a = 1/(1+z)$



SNe (type Ia and core-collapse) are also:

Element factories →

Cosmic ray accelerators…

Sources of kinetic energy regulating star formation

But …

Nobody knows exactly WHAT is exploding and HOW!

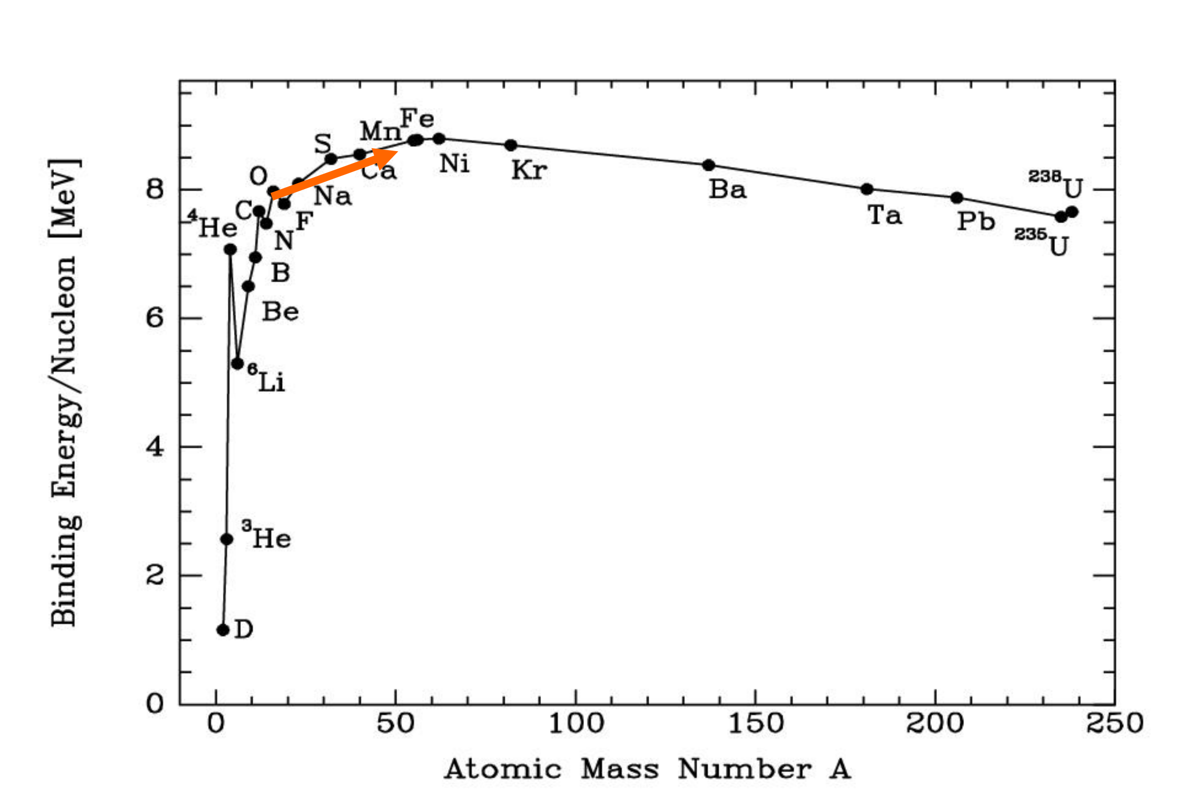
What?: (who are the progenitors)

How?: (pre- and post-explosion physics: accretion, common-envelope phase, ignition, combustion, environmental dependences)

Type-Ia SNe: What do we know?

thermonuclear explosions

C,O ⟶ Ni



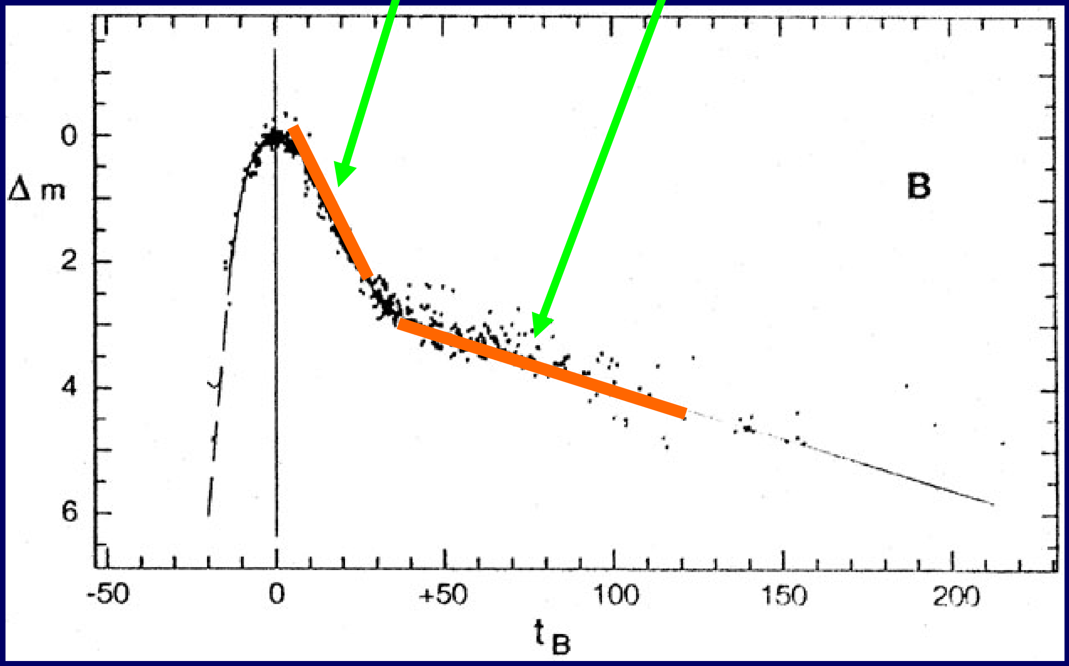
How do we know this?

1. no H, He in the spectrum.

2. optical luminosity from radioactive decay of ~0.7 M⊙ of

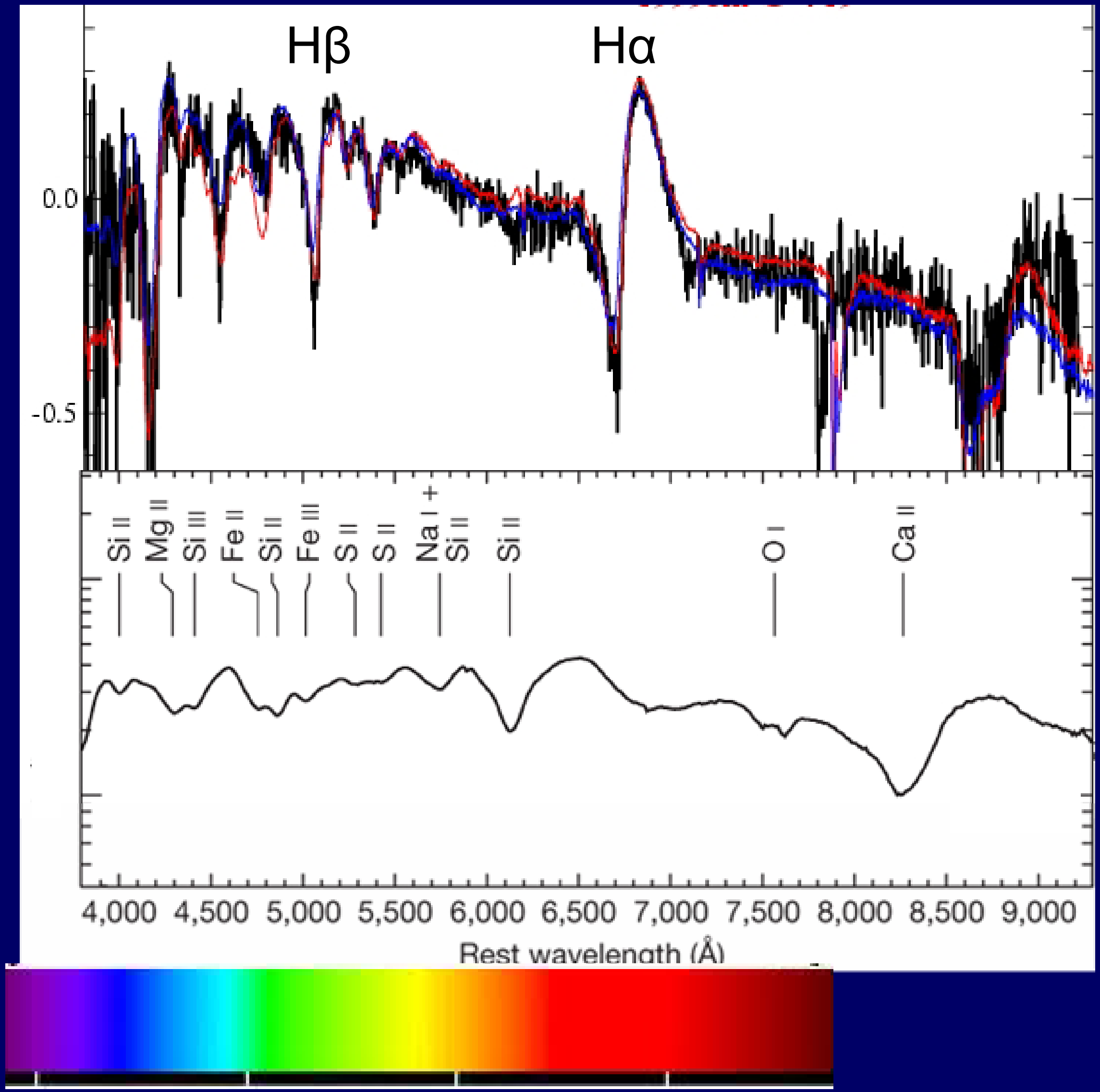
$^{56}Ni \rightarrow ^{56}Co \rightarrow ^{56}Fe$

τ=9 d   τ=114 d



2.5 log flux

Time (days)



Core-collapse SN

Type-Ia SN

How do we know this?

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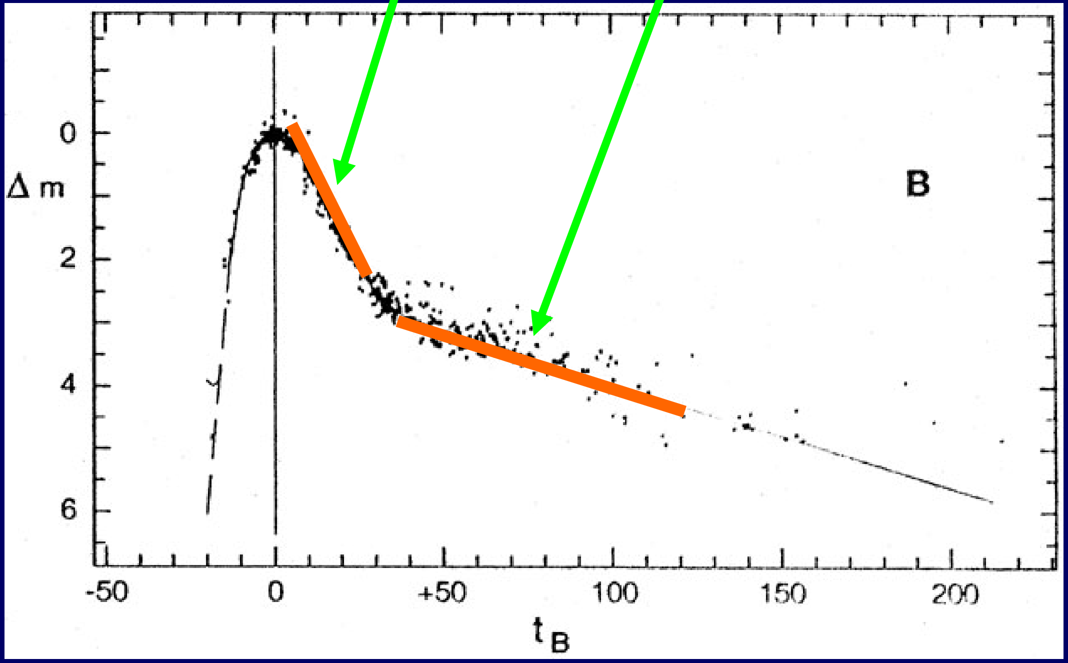
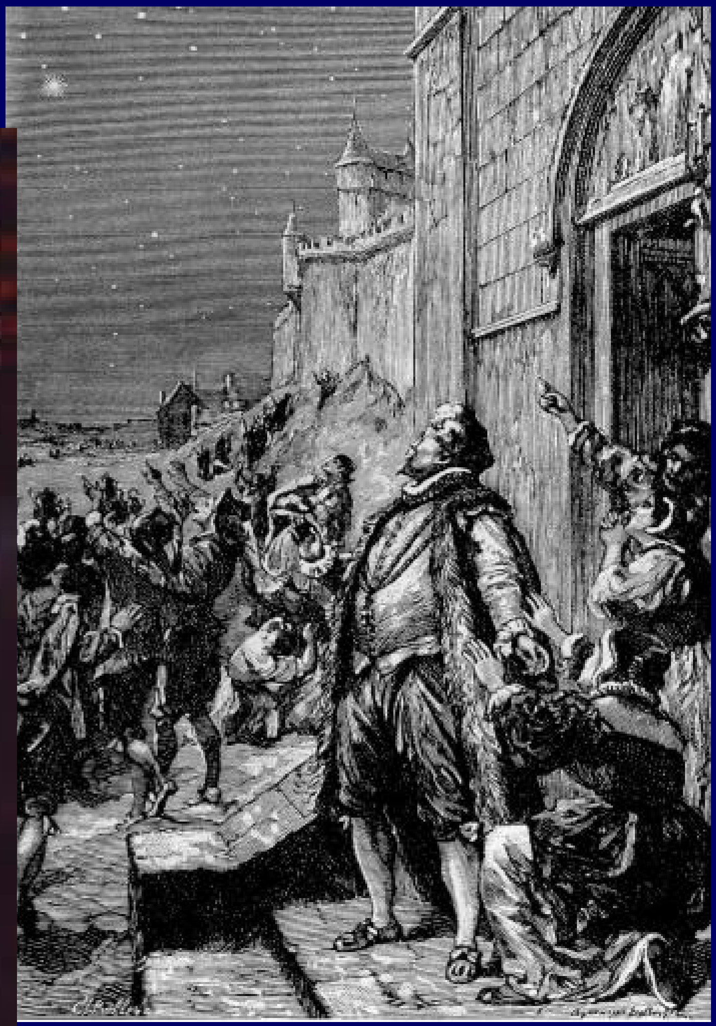
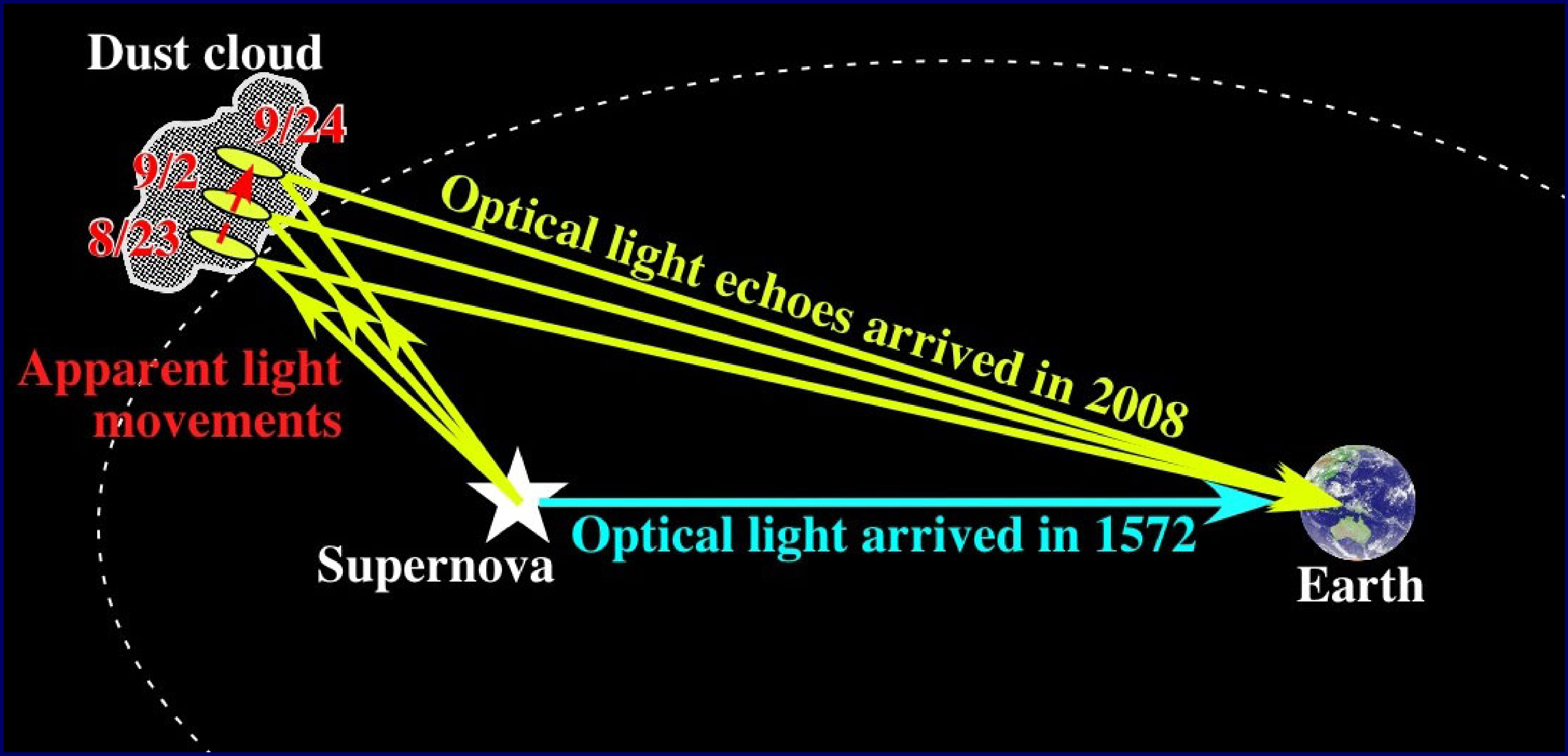


2.5 log flux

Time (days)

The most recent certain type-Ia SN nearby:
SN 1572 (Tycho's)

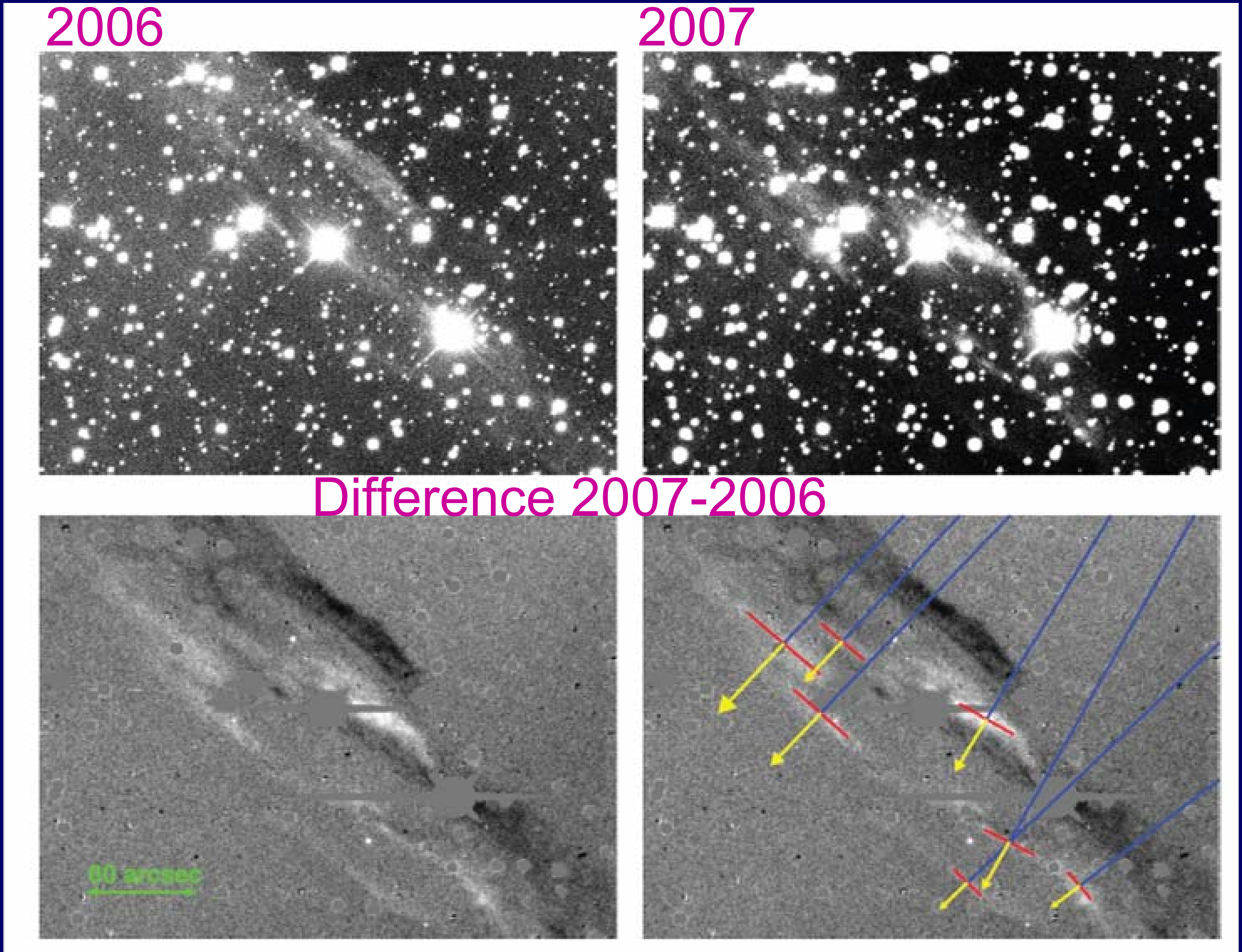




Dust cloud
9/24
9/2
8/23
Optical light echoes arrived in 2008
Apparent light movements
Supernova
Optical light arrived in 1572
Earth

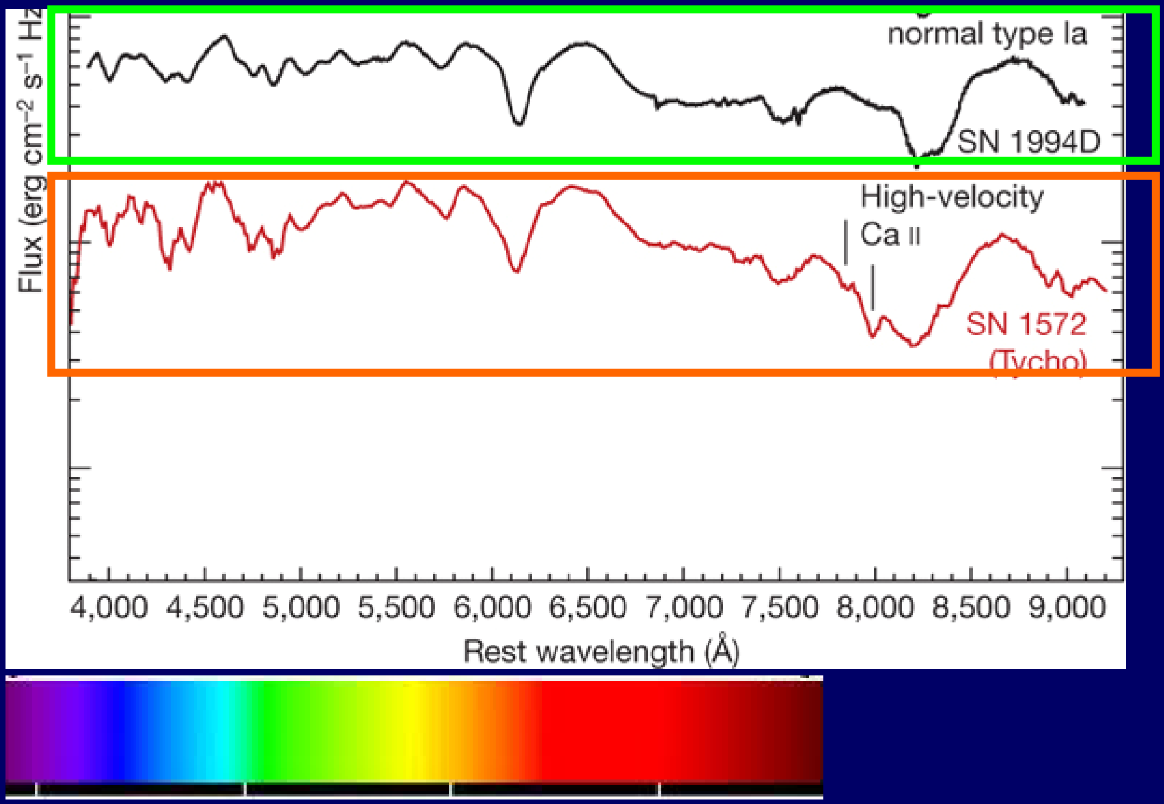
Rest et al. (2008):

discovery of light echoes of Tycho's SN



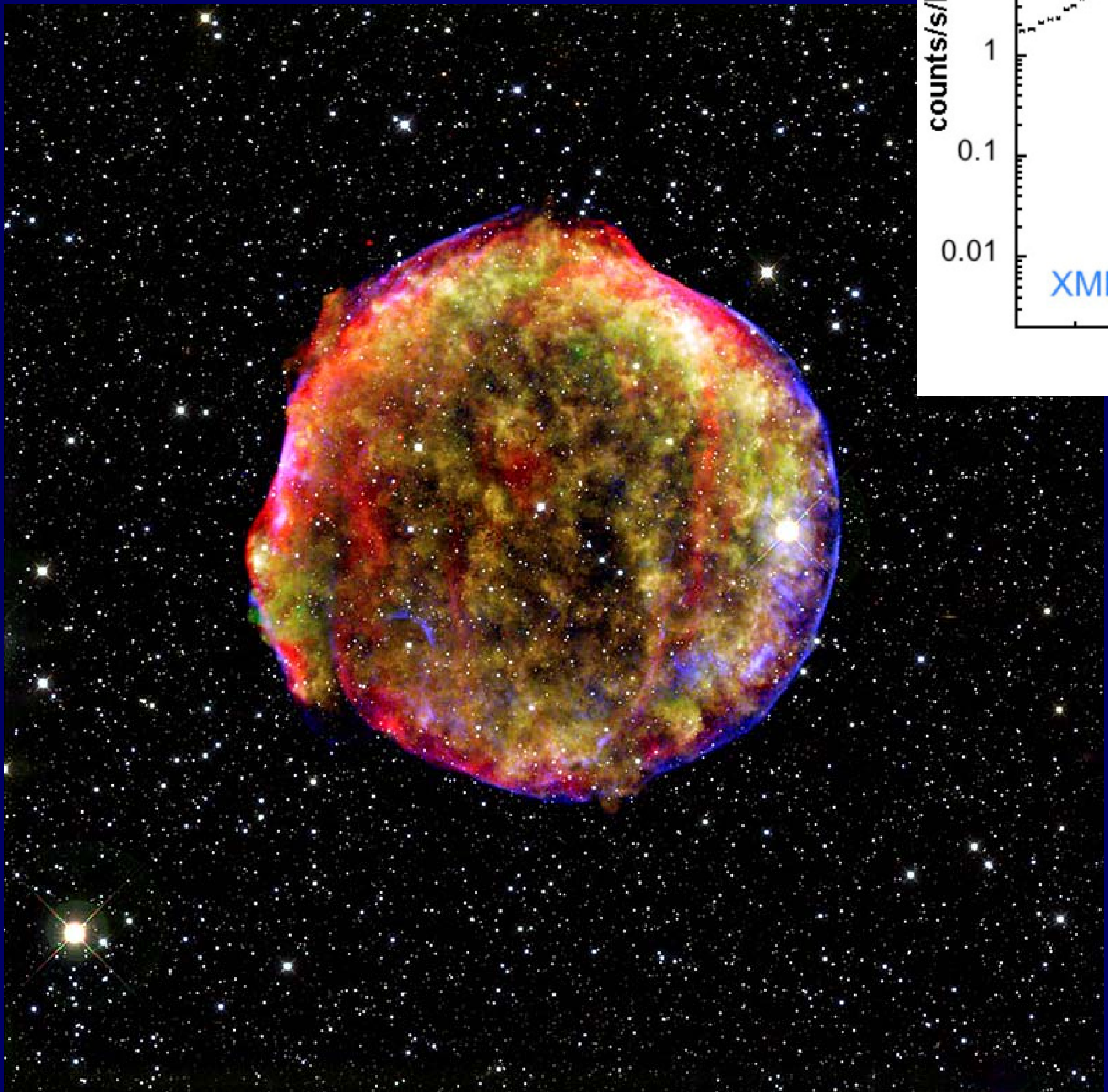
The echo has the spectrum of a normal SN Ia (Krause et al. 2008)

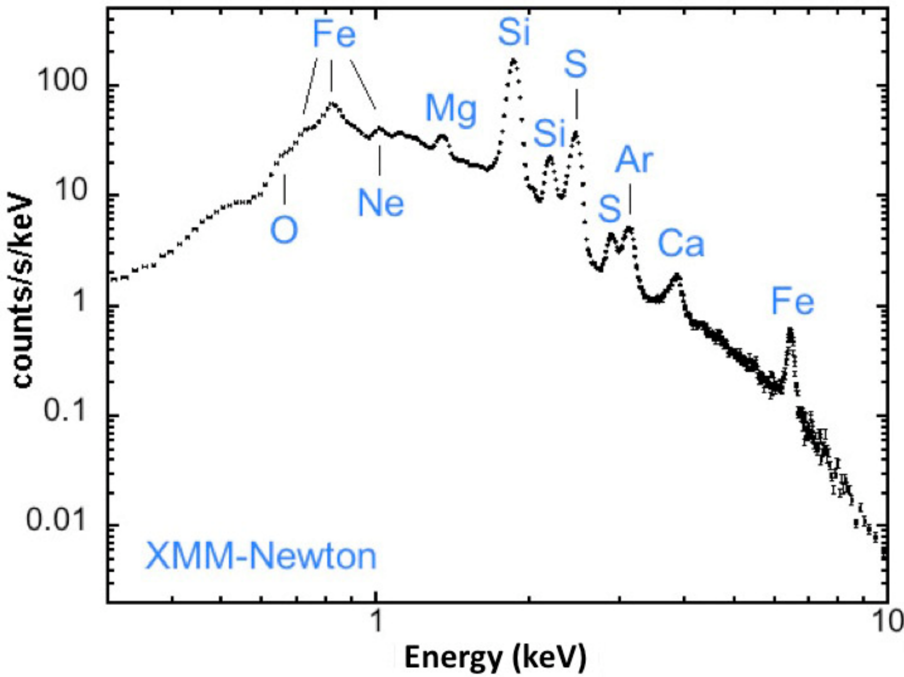
Spectrum of SN1994D



spectrum of the echo

Tycho's SN remnant, after 438 years

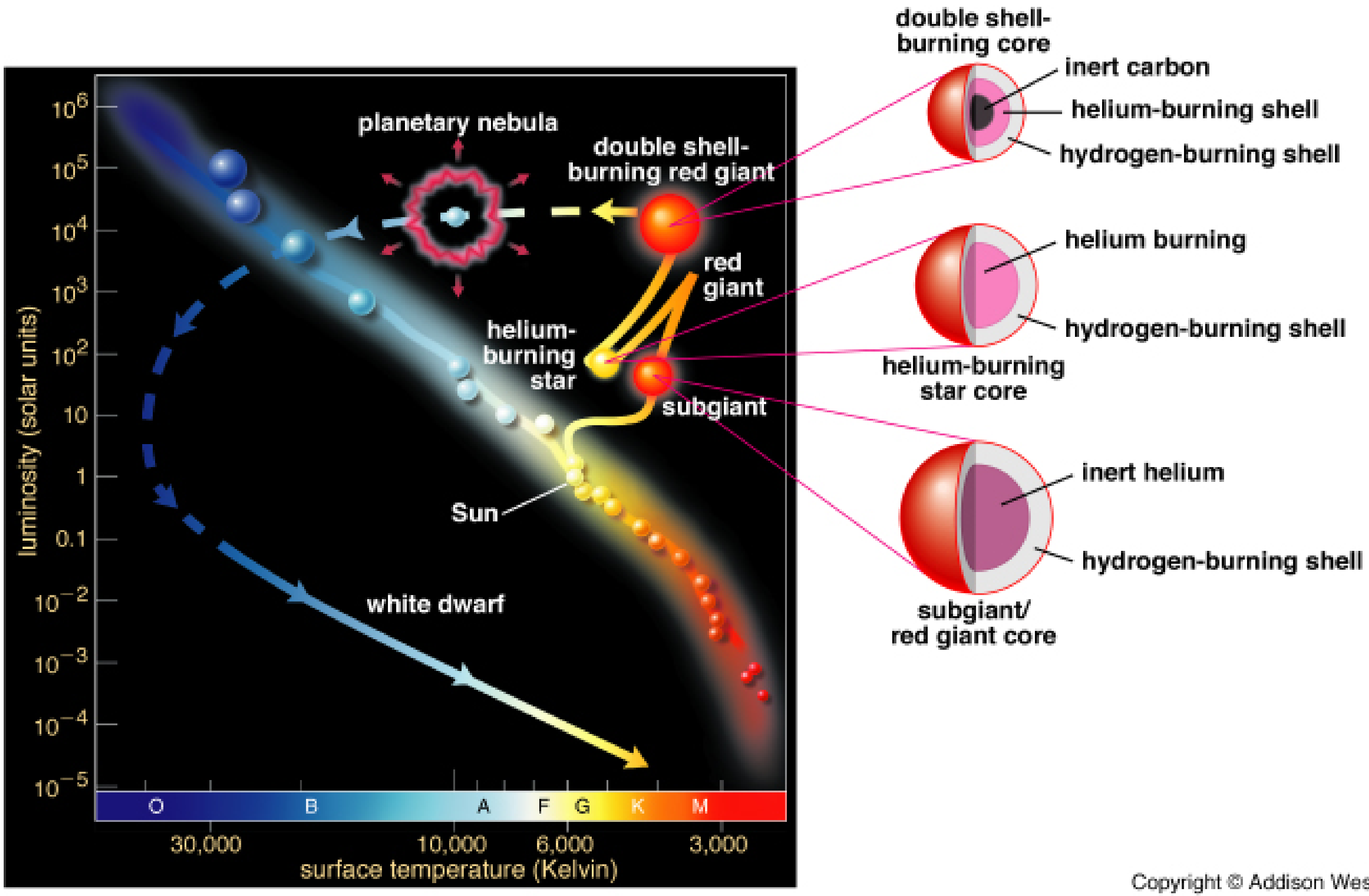




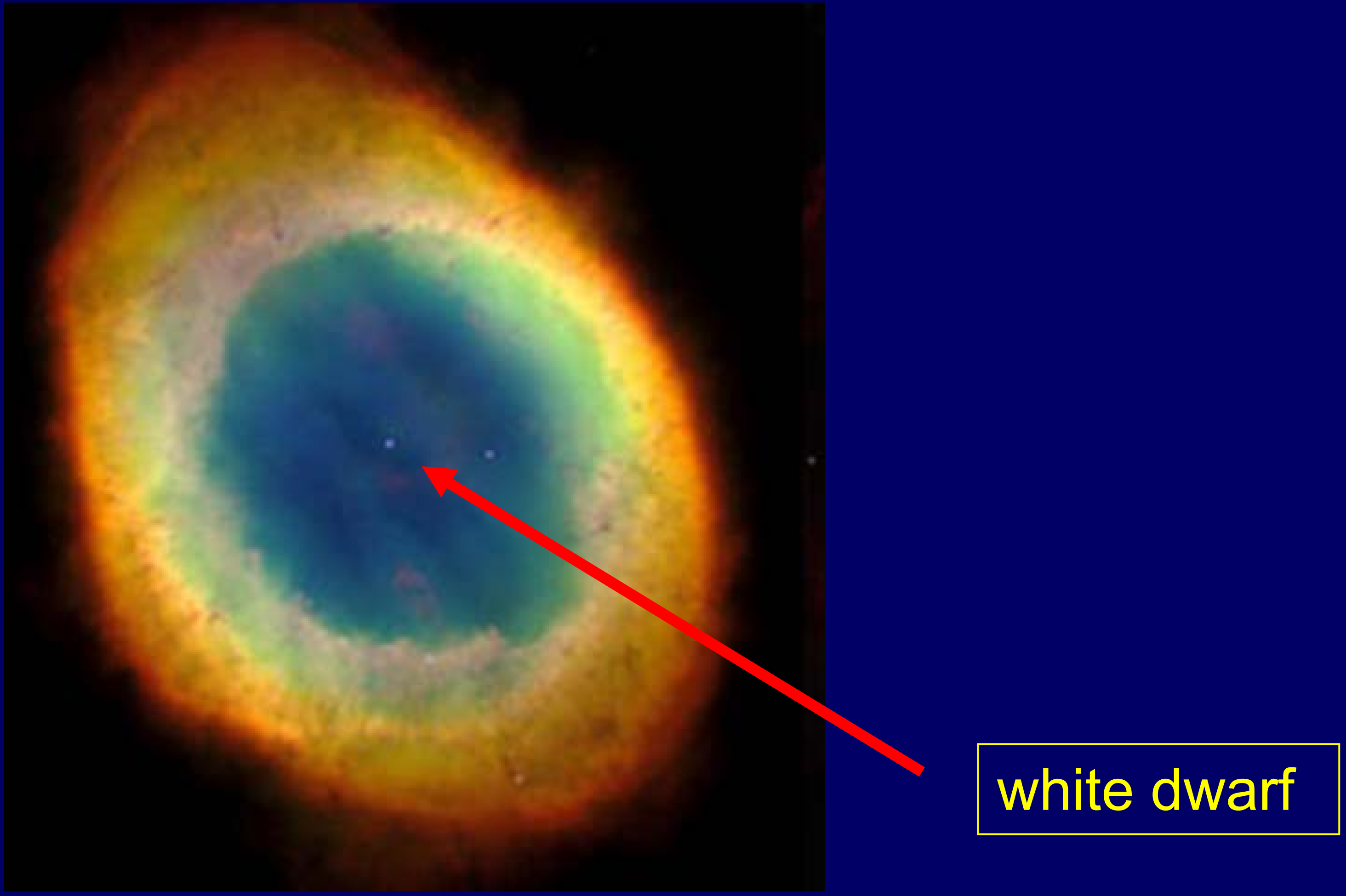
So, how to create?:

1. ~0.7 M⊙ of ^{56}Ni,
2. no traces of H,He,
3. kinetic energy of ejecta ~10^{51} erg
4. in regions with no massive stars.

Blow up a ~1.4 M⊙ white dwarf! (Hoyle & Fowler 1960)



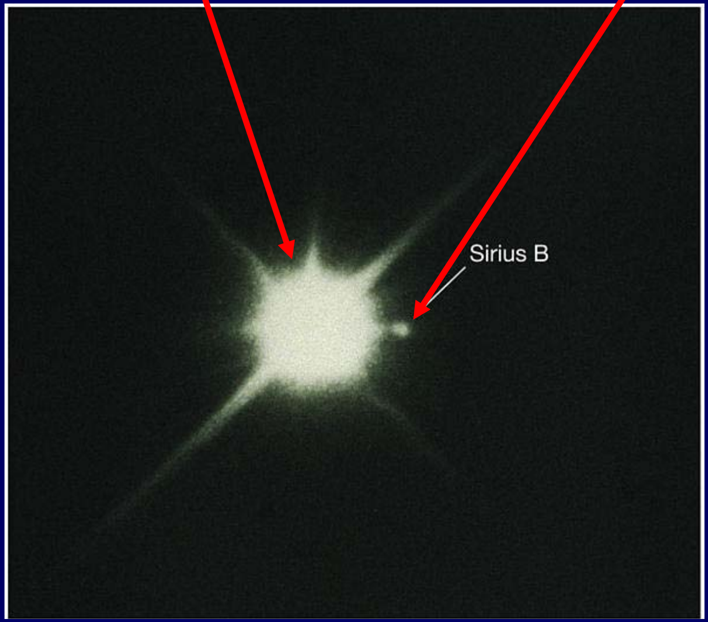
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^−2
10^−3
10^−4
10^−5
planetary nebula
double shell-
burning red giant
red
giant
helium-
burning
star
subgiant
Sun
white dwarf
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
surface temperature (Kelvin)
double shell-
burning core
inert carbon
helium-burning shell
hydrogen-burning shell
helium burning
hydrogen-burning shell
helium-burning
star core
inert helium
hydrogen-burning shell
subgiant/
red giant core



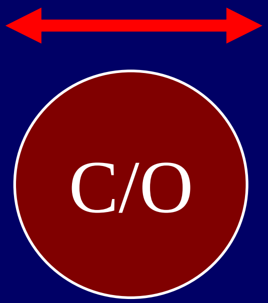
WD is made almost entirely of C,O.

Sirius A
Normal star

Sirius B white dwarf



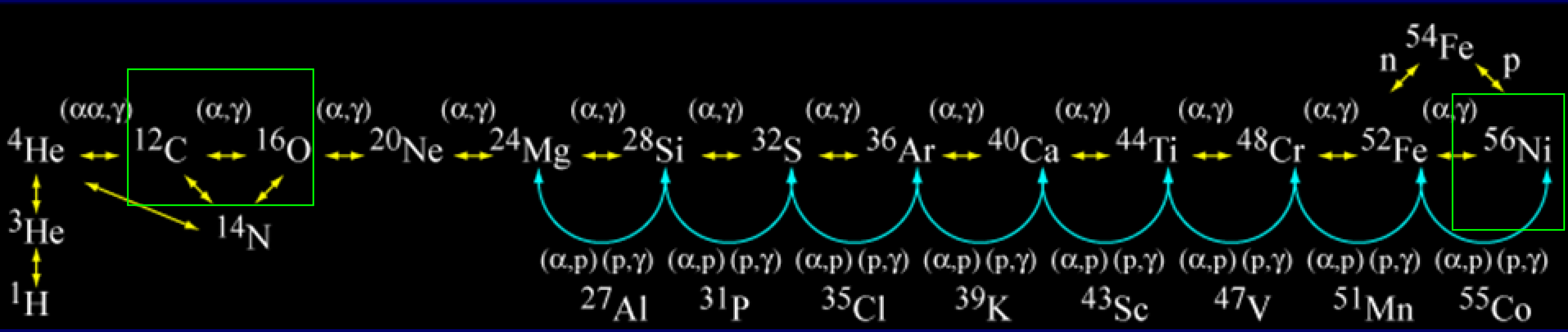
10,000 km



M ~ 1 M⊙

Density~ 1 ton/cm^3

EOS: degenerate electron gas.
If ignited, unstable to thermonuclear runaway!



^{54}Fe
n
p
(αα,γ)
(α,γ)
^{4}He
^{12}C
^{16}O
^{20}Ne
^{24}Mg
^{28}Si
^{32}S
^{36}Ar
^{40}Ca
^{44}Ti
^{48}Cr
^{52}Fe
^{56}Ni
^{3}He
^{14}N
^{1}H
(α,p) (p,γ)
^{27}Al
^{31}P
^{35}Cl
^{39}K
^{43}Sc
^{47}V
^{51}Mn
^{55}Co

Energy Budget:

E_{nuc} (0.8 Mo C,O → Fe) = 2×10^{51} ergs

E_{bind} (1.4 Mo WD) $\approx 0.5 \times 10^{51}$ ergs ☑

$$\text{v} \sim \sqrt{2E_{\text{K}}/M_{\text{ch}}} \sim 10^9 \text{cm/s}$$ ☑

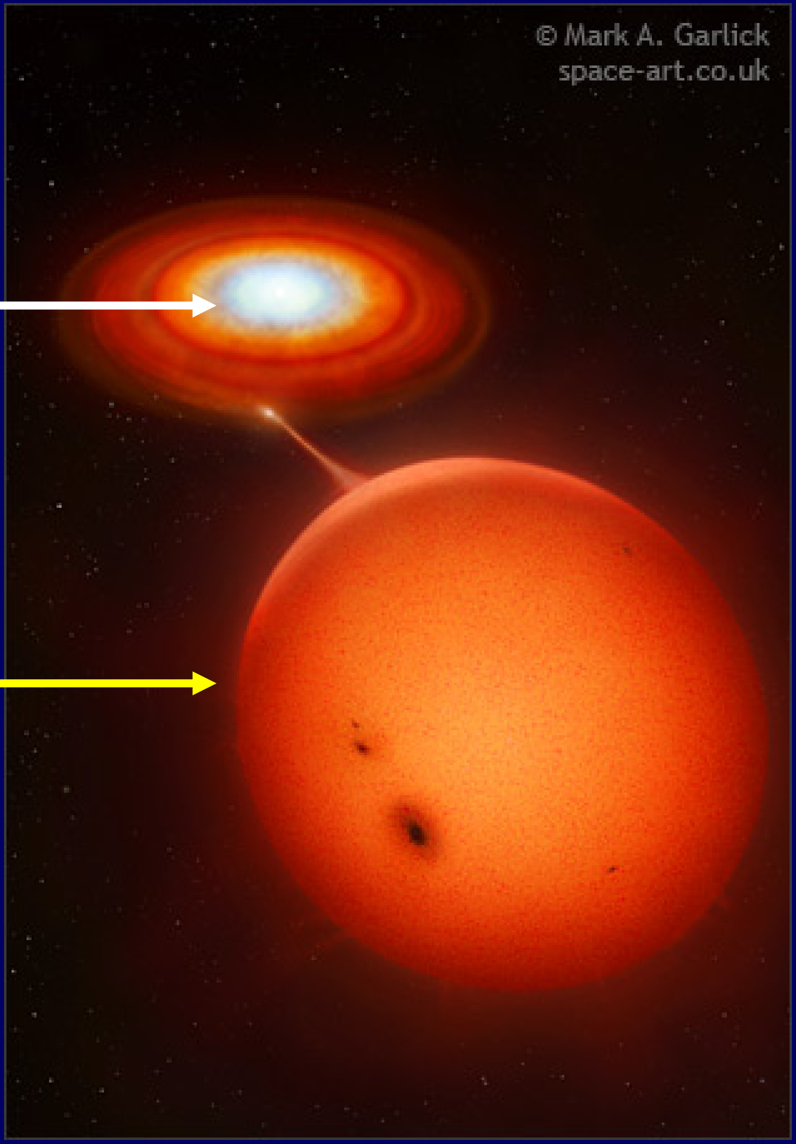
But, how to ignite the WD?

C/O

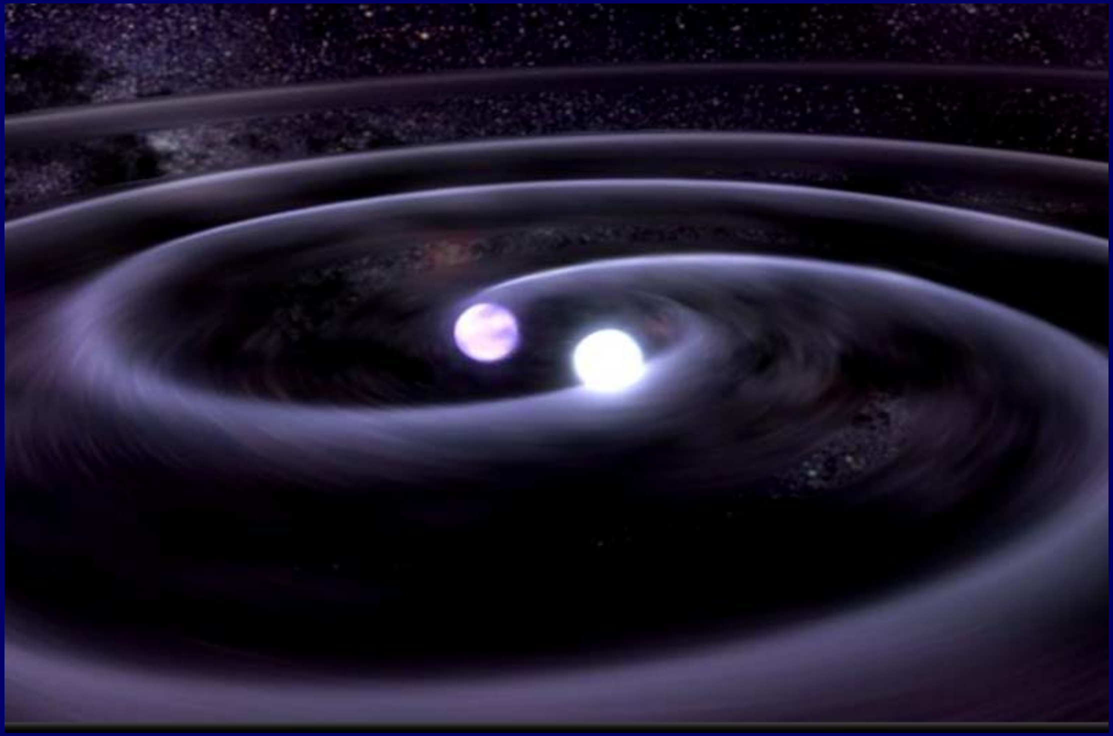
“single degenerate” (“SD”) (Whelan & Iben 1974)

WD

Main sequence
or red-giant



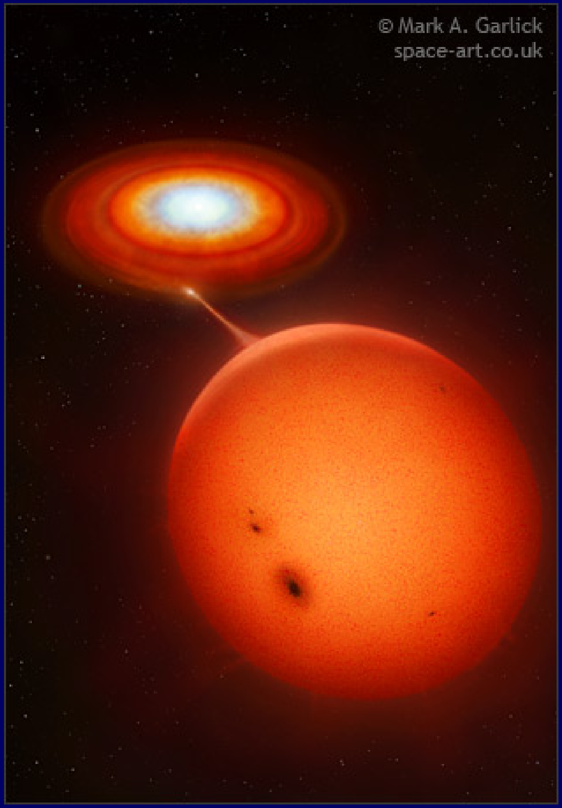
“double degenerate” (“DD”) (Webbink 1984; Iben & Tutukov 1984)

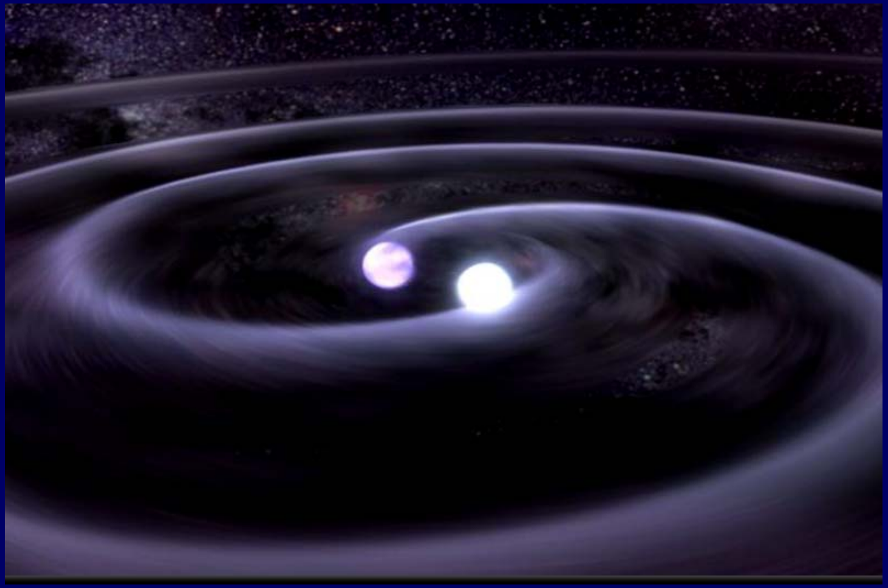


The progenitor question:
What's exploding?

?

?





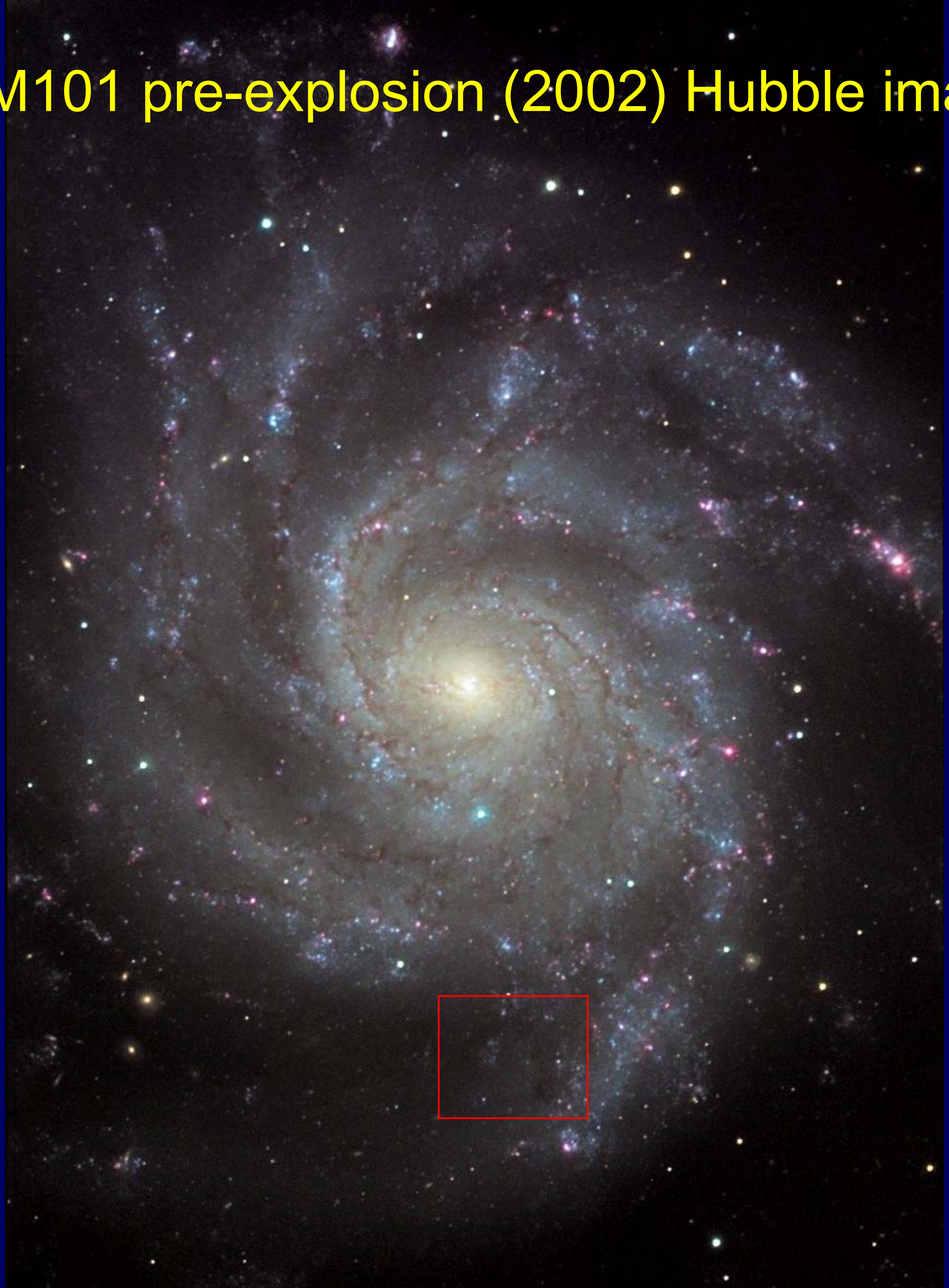
Other new ideas (Distefano+11; Justham 11; Kashi&Soker 11):
SD/DD "on hold"

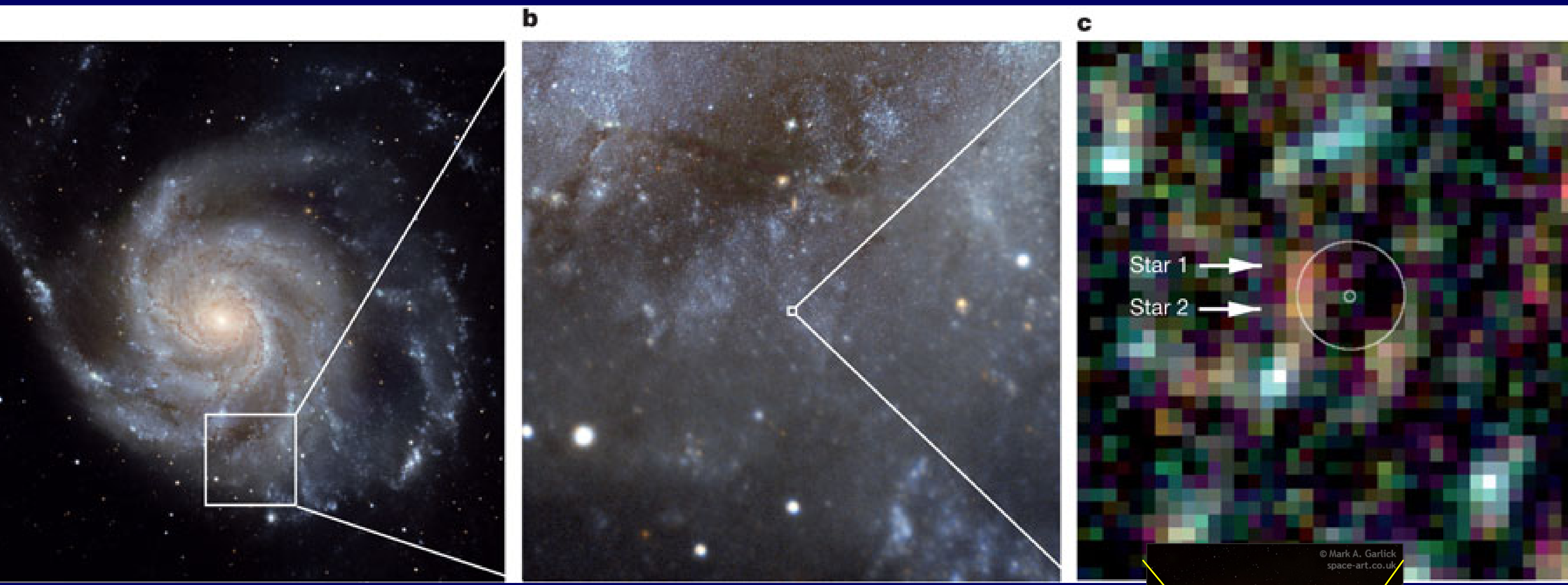
Problems with both progenitor scenarios…

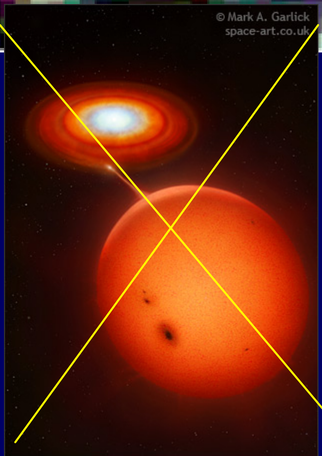
August 2011: SN 2011fe in M101
(only 20M light years away!)


© Yuri Beletsky

M101 pre-explosion (2002) Hubble image

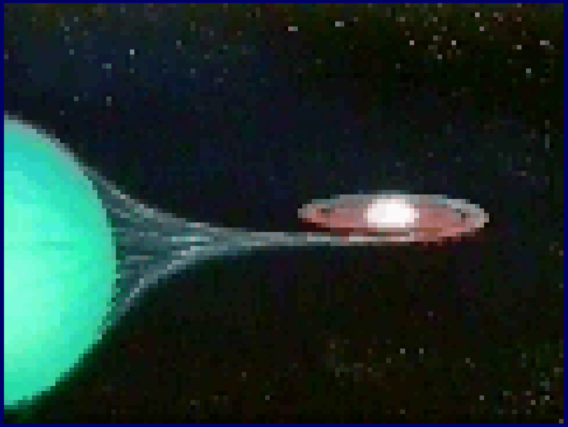




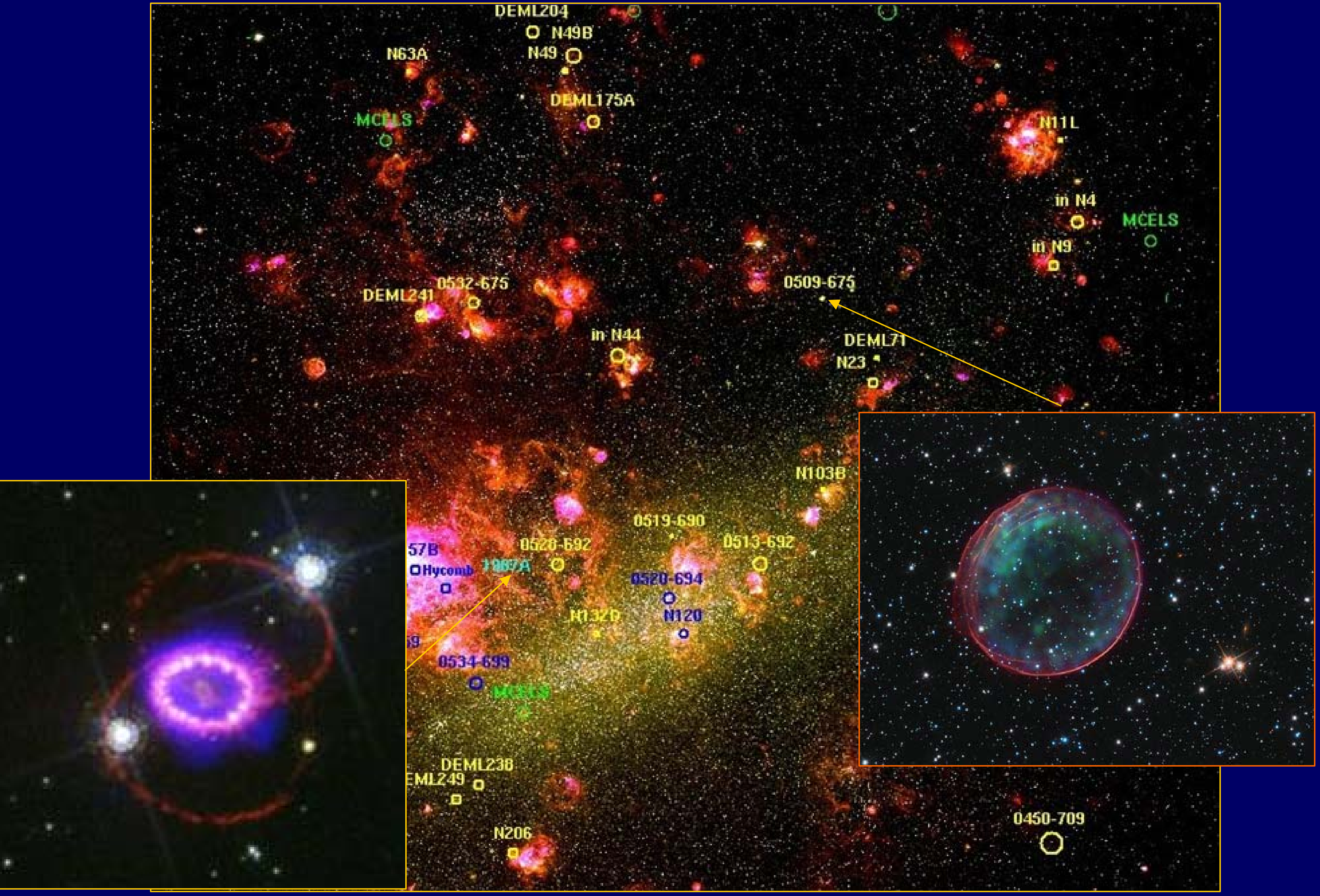


(Li et al. 2011) :

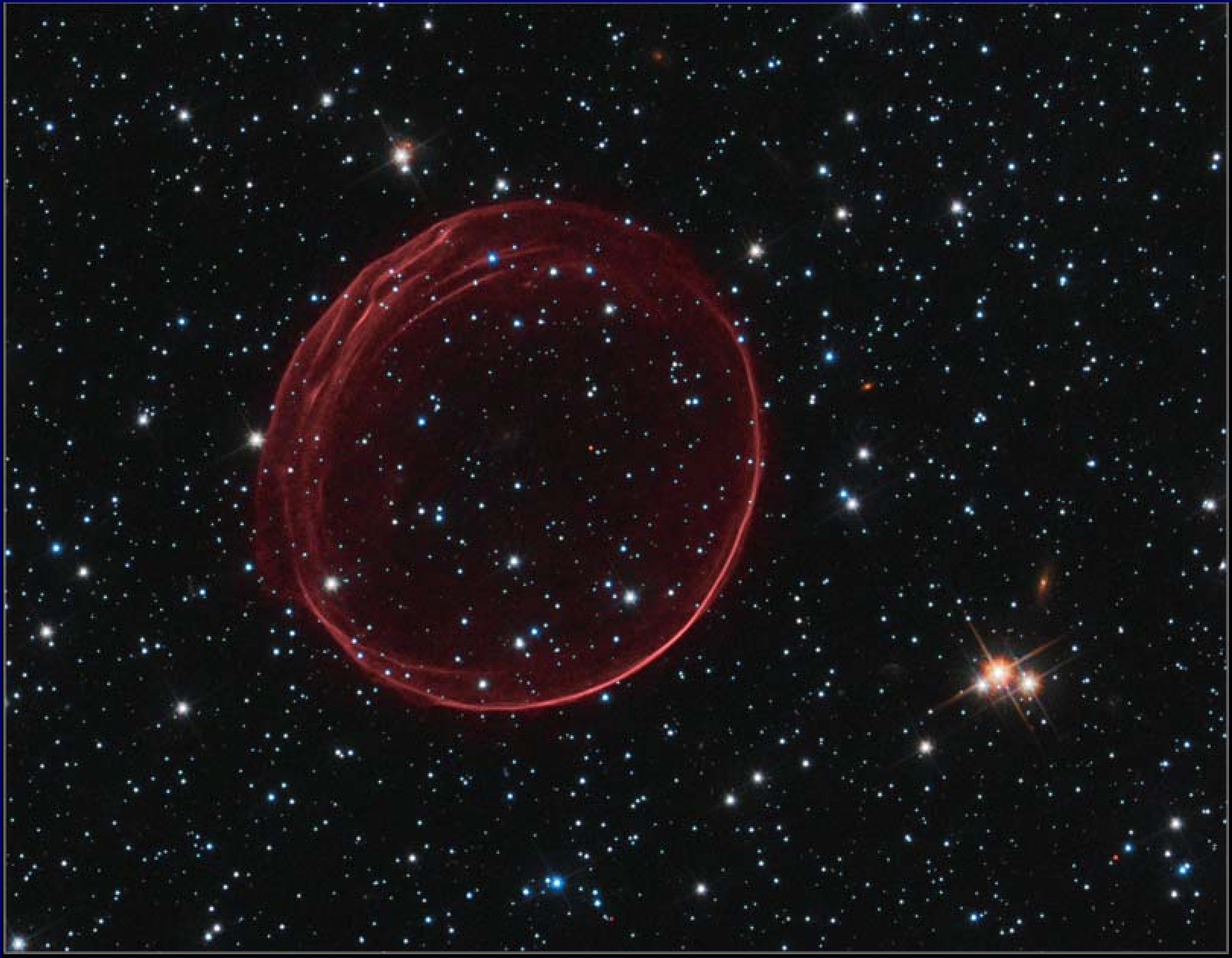
Donor star was NOT a red giant

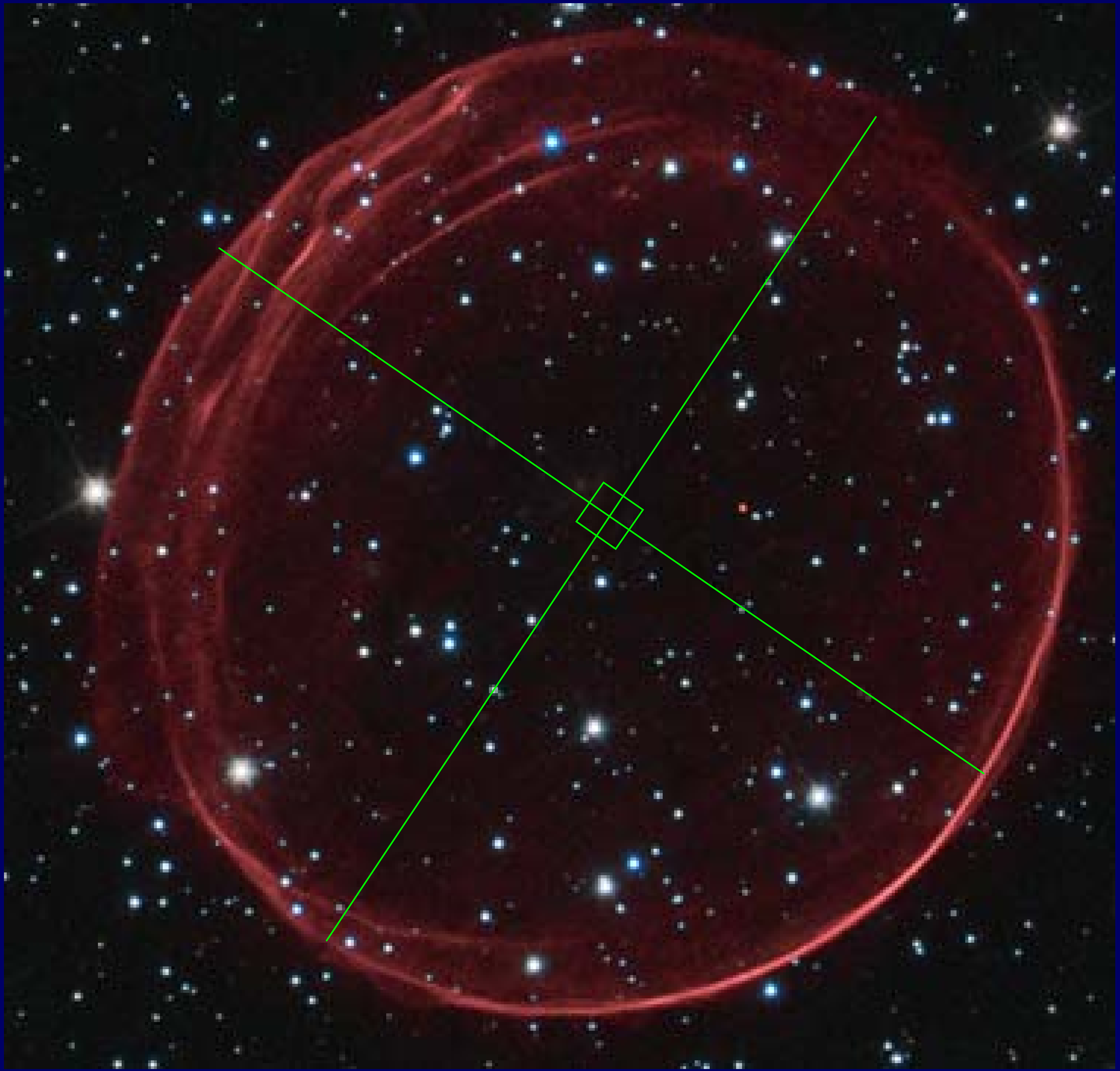


Problems with both progenitor scenarios…

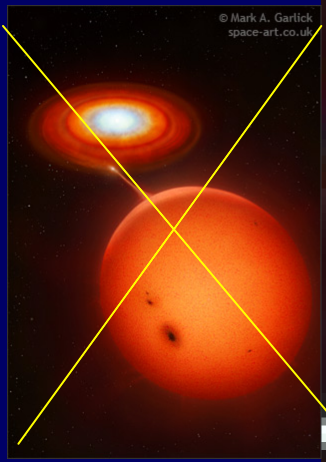


A type-Ia supernova from ca. 1600, 400 years later





Schaefer & Pagnotta 12



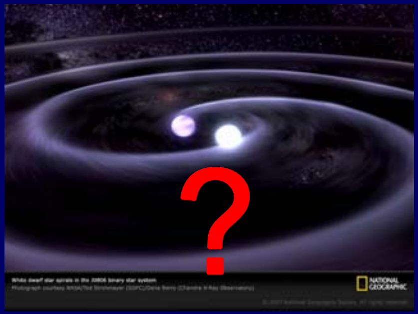
No companion star left behind! (down to 0.5 M⊙)

Problems with both progenitor scenarios…

DD model:

Theory:

Merger leads to core-collapse, not SN Ia? (Nomoto & Iben 1985, Guerrero+ 2004, but Piersanti+ 2003)



Tidal disruption, accretion of lower-mass WD;

Off-center C ignition at low density, stable burning;

ONe WD;

Continued stable accretion, burning to Fe;

Neutronization, core collapse.

Clues to progenitors can be obtained by measuring SN Rates

(also get cosmic timescales for element enrichment, etc.)

To measure a SN rate, need to discover some SNe.

$$\frac{1\ \text{SN}}{200\ \text{yr galaxy}} \times \frac{2}{50}\ \text{yr} = \frac{1\ \text{SN}}{5{,}000\ \text{galaxies}}$$

SN is visible for ~2 weeks

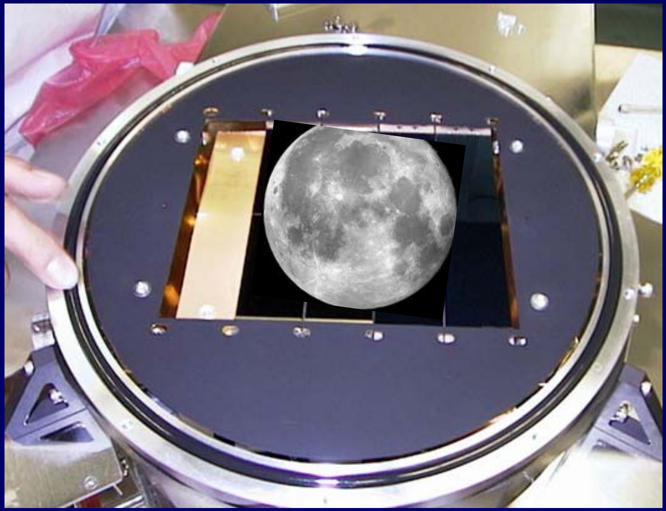
SNe visible at a given time

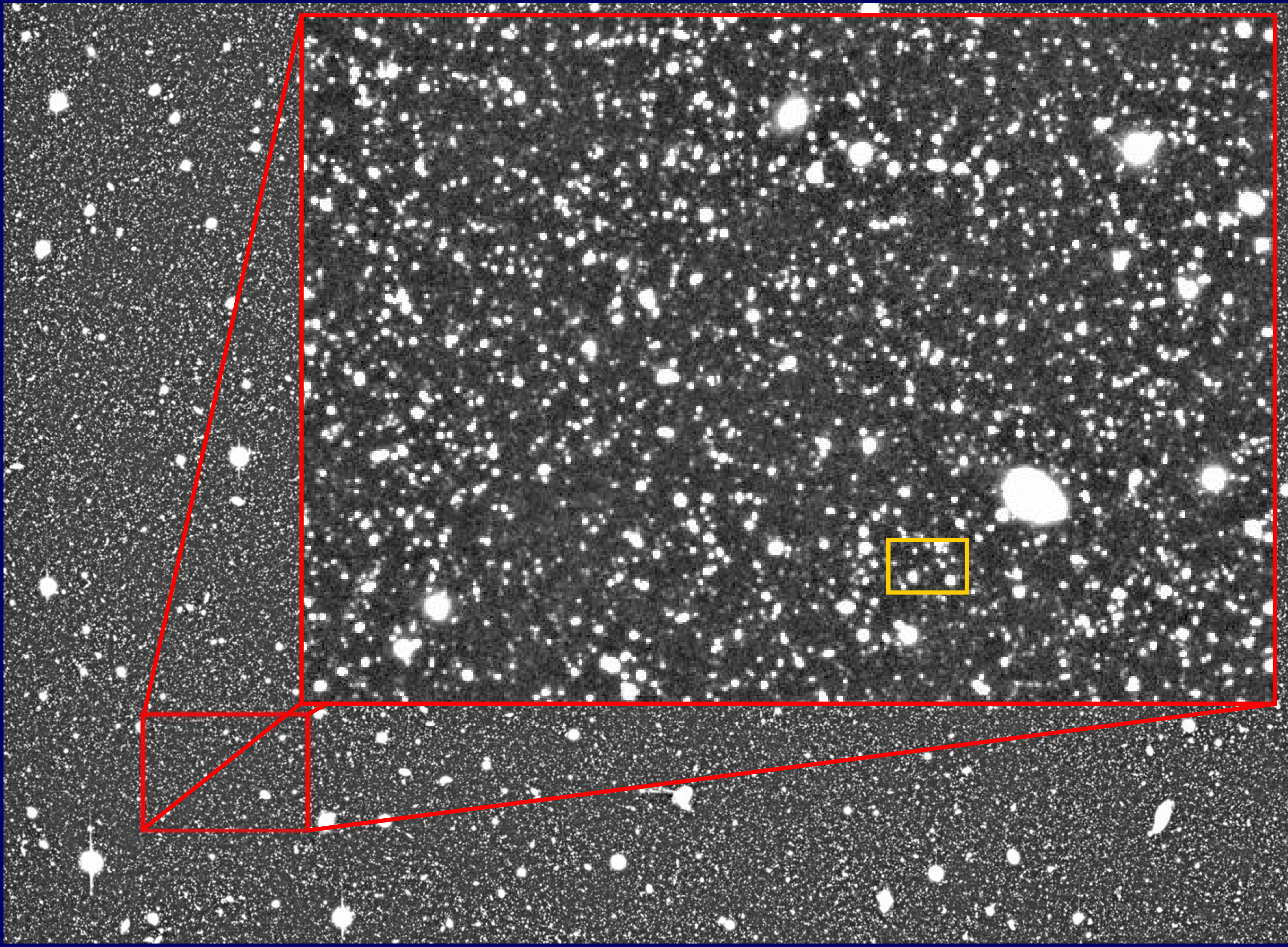

Subaru
2 Kecks
Gemini North

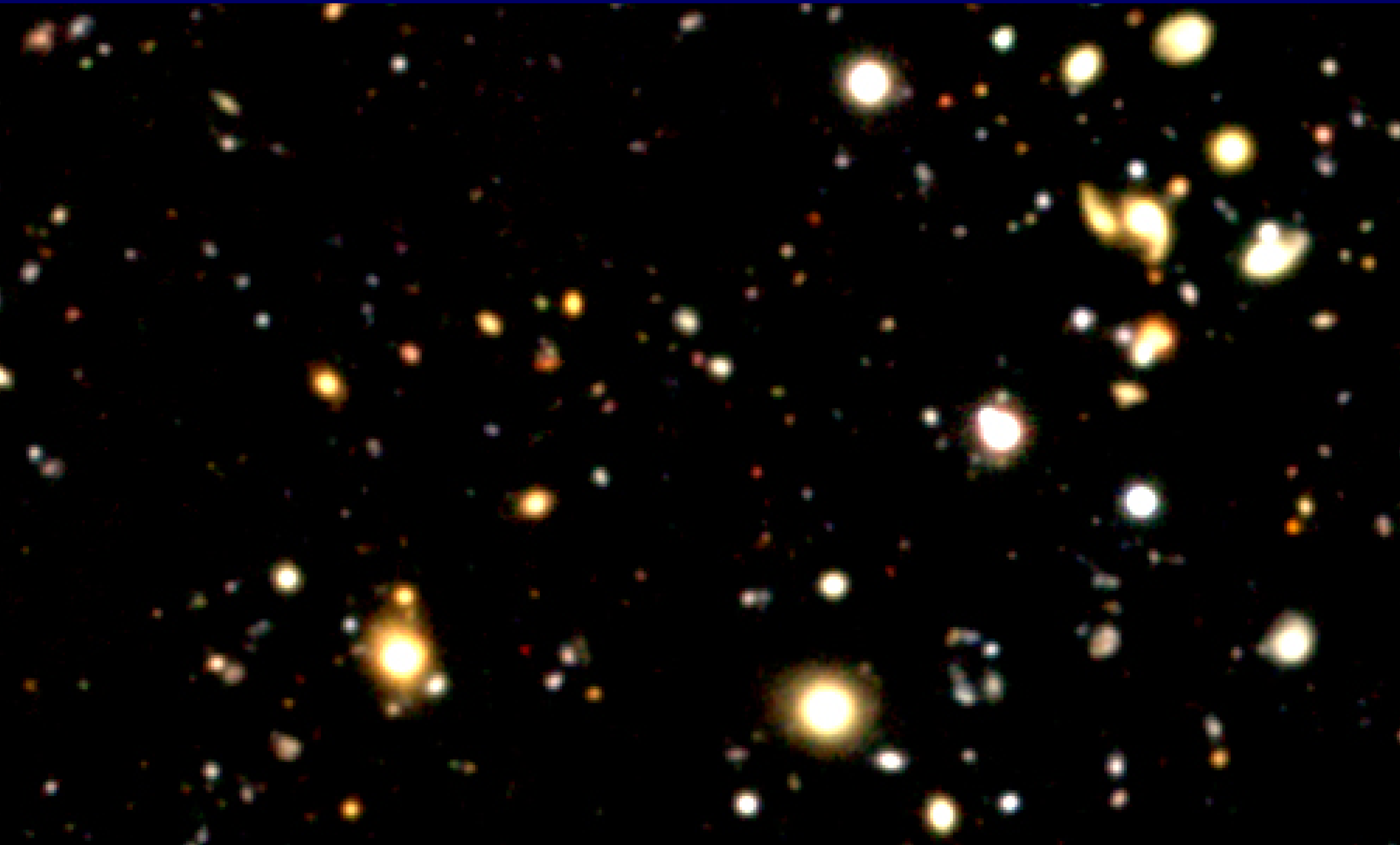
SN rate at high z from the Subaru Deep Field

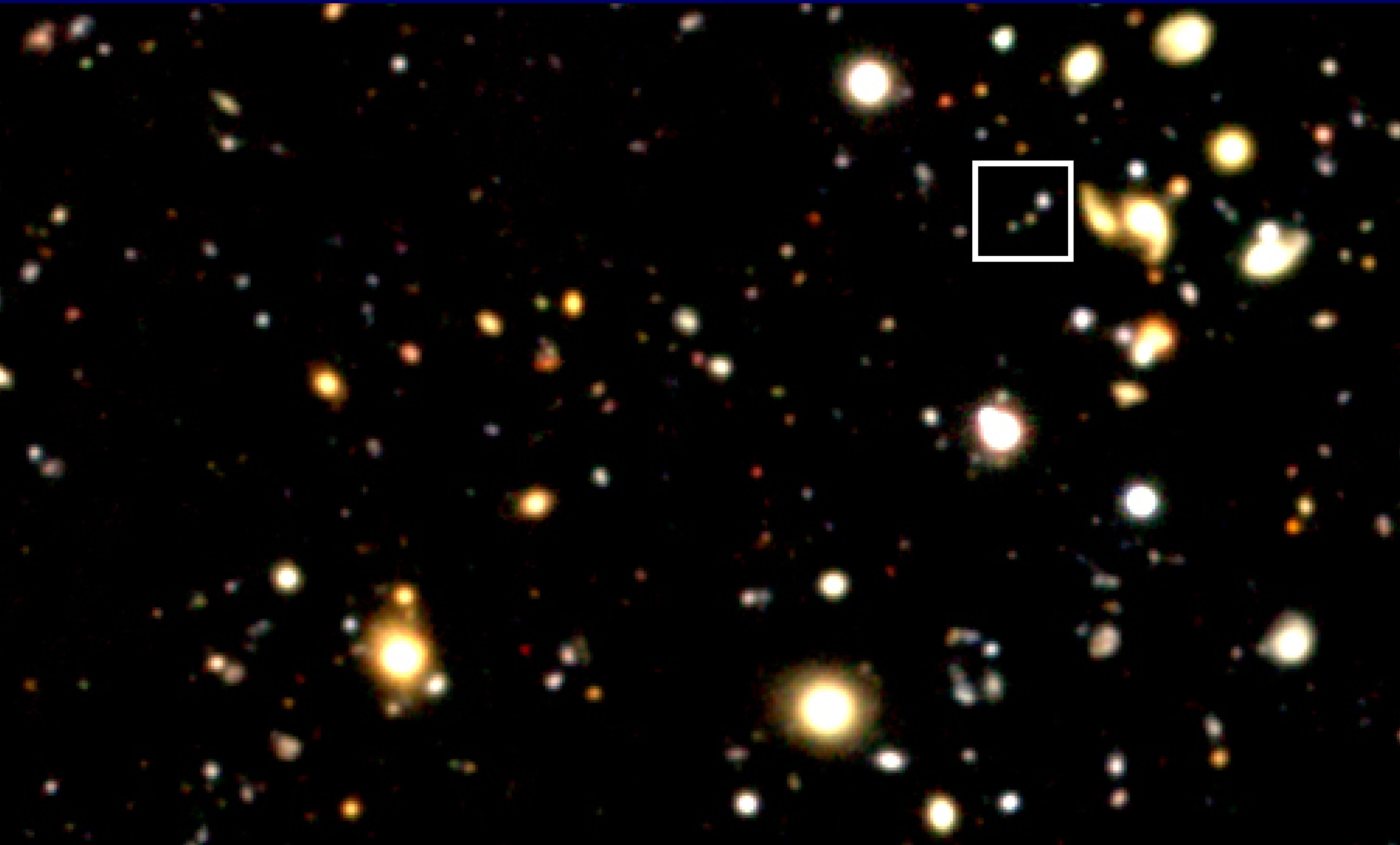
Poznanski et al. 2007,
Graur et al. 2011

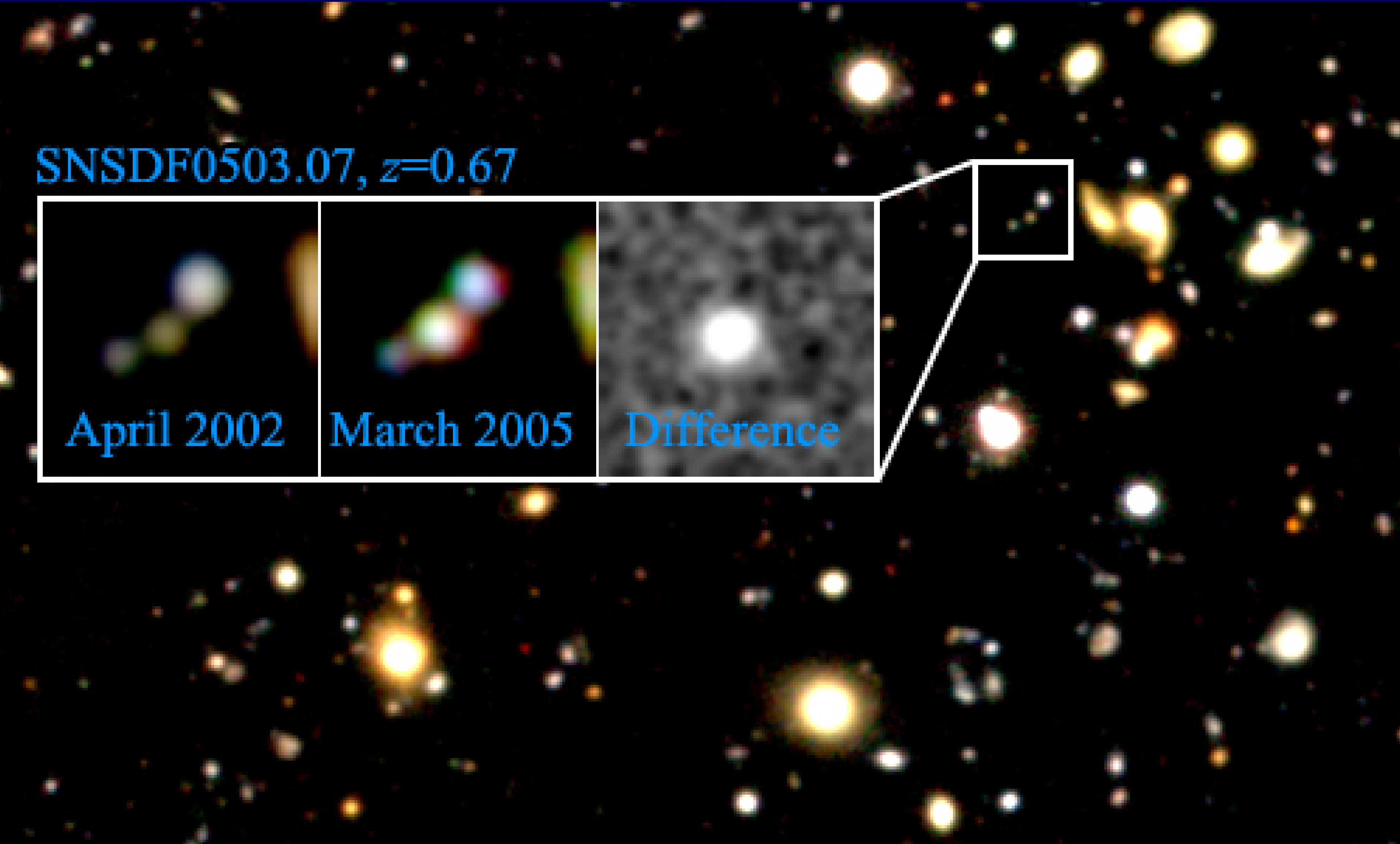
- 4x(2-night) runs
- Stare at the 0.25 deg^2 SDF:
  r, i ~ 27 mag, z ~ 26 mag

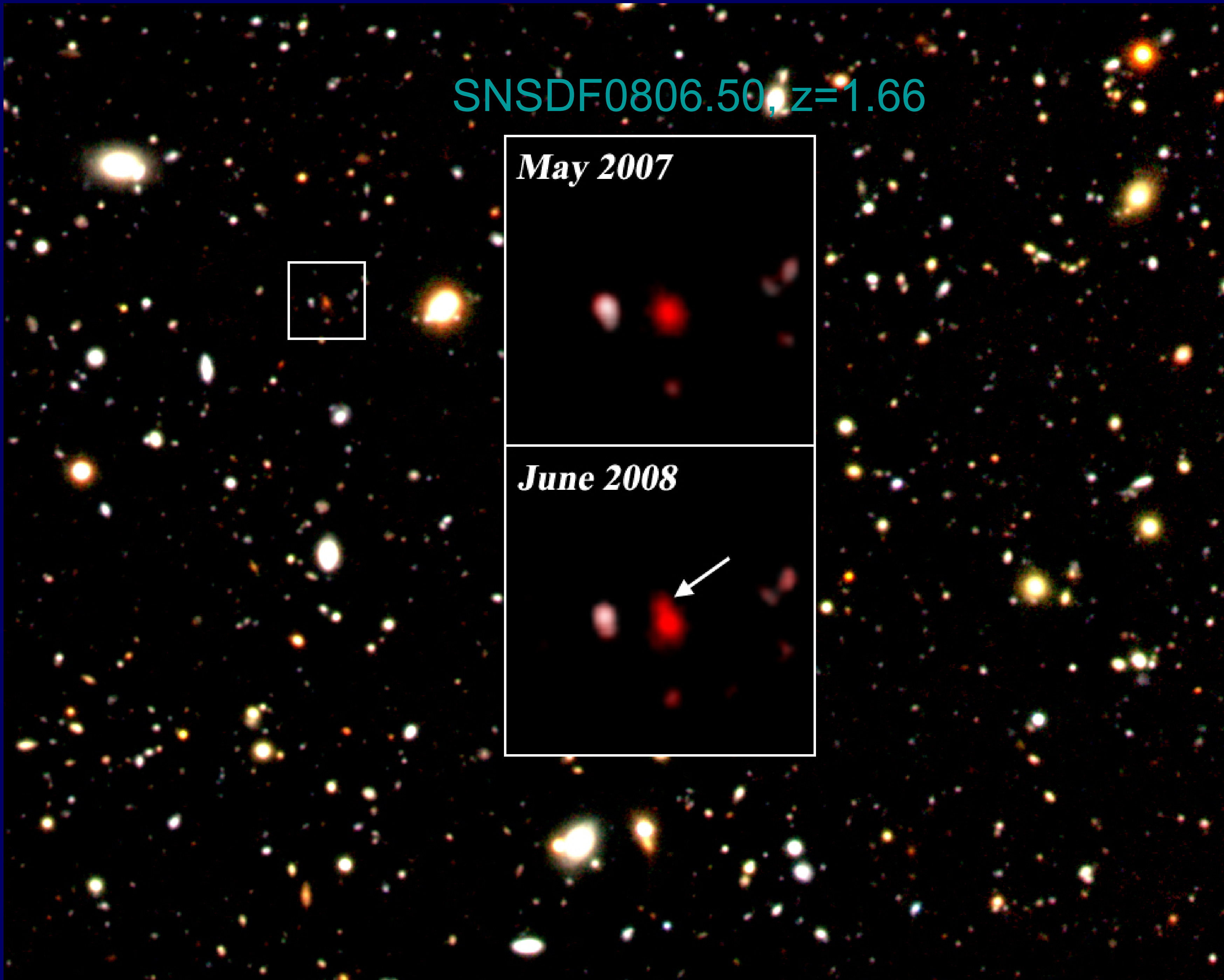


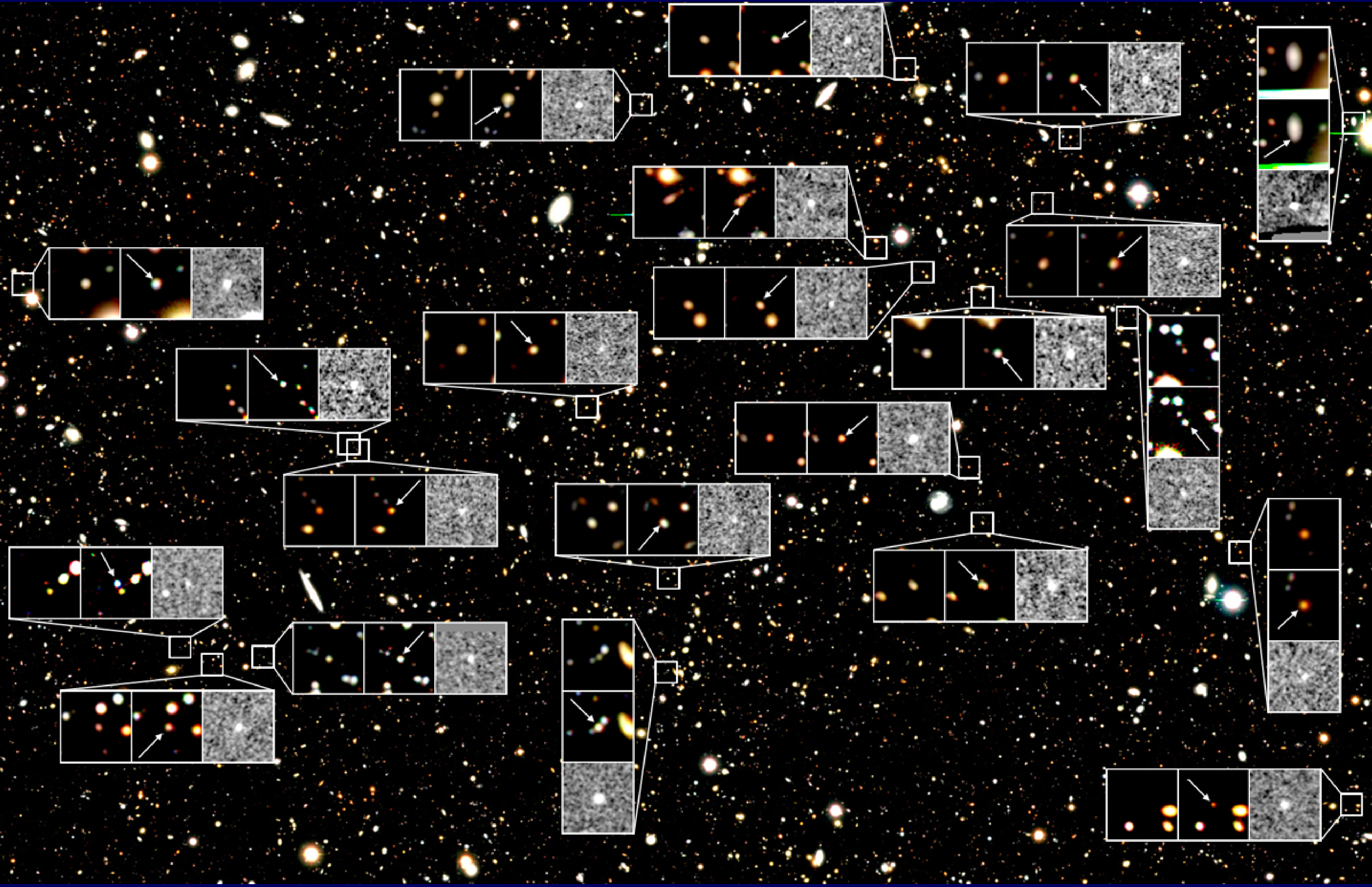







SNSDF0503.07, z=0.67
April 2002
March 2005
Difference


SNSDF0806.50, z=1.66
May 2007
June 2008



How to measure a SN rate?

$$R = \frac{N_{\rm SN}}{\sum_i t_i},$$

SN rate per galaxy

Visibility time (“control time”)

IMPORTANT!

SN Ia “delay time distribution” (DTD):

=

the hypothetical SN Ia rate vs. time following a short burst of star formation.

Different progenitor scenarios predict different DTD

SN Ia "delay time distribution" (DTD):

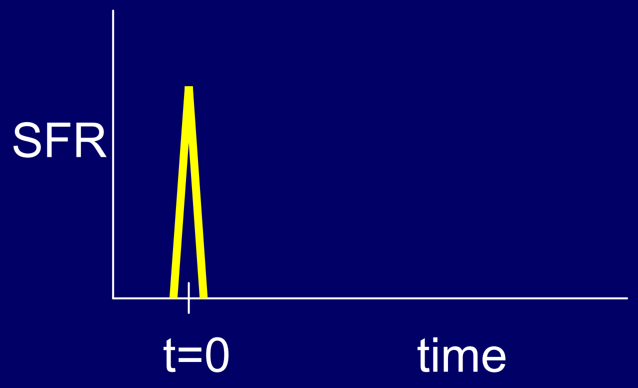
IMPORTANT!

=

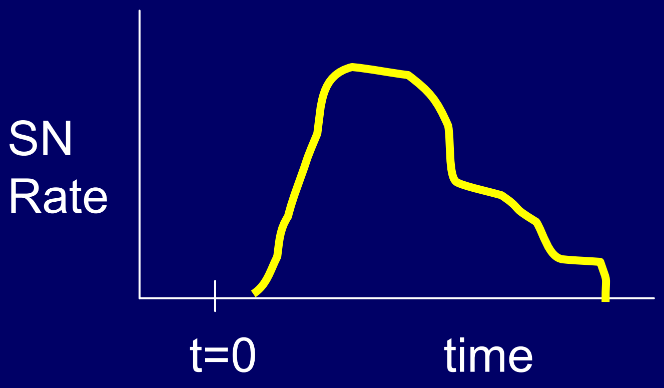
the hypothetical SN Ia rate vs. time following a short burst of star formation.

Different progenitor scenarios predict different DTD (talks tomorrow by Ruiter and Toonen)

Star formation rate



SN DTD



e.g., Double-Degenerate scenario.

Consider population of binary WDs.

Time until merger of each pair (gravitational wave losses):

$$t \sim a^4.$$

If the separations are distributed as a power law

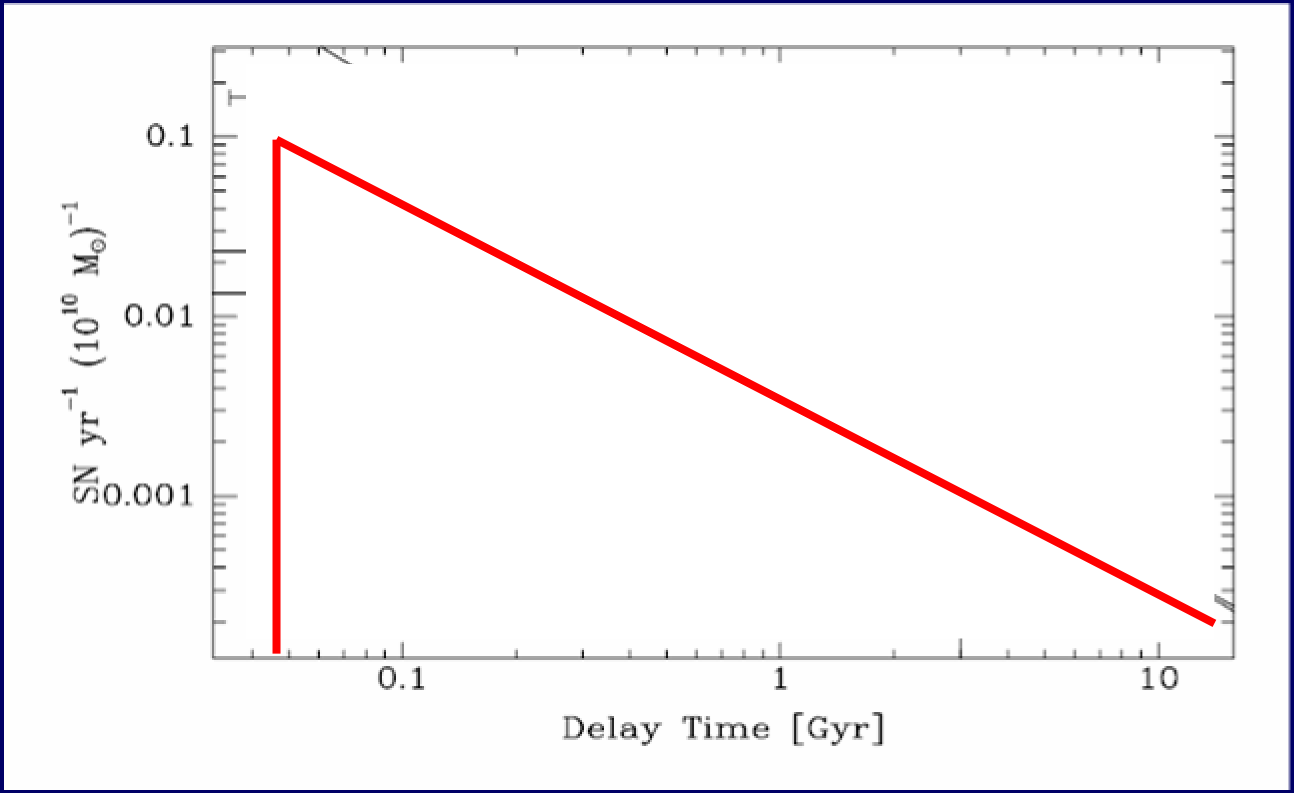
$$\frac{dN}{da} \sim a^\epsilon,$$

then the event rate will be

$$\frac{dN}{dt} = \frac{dN}{da}\frac{da}{dt} \sim t^{(\epsilon-3)/4}.$$

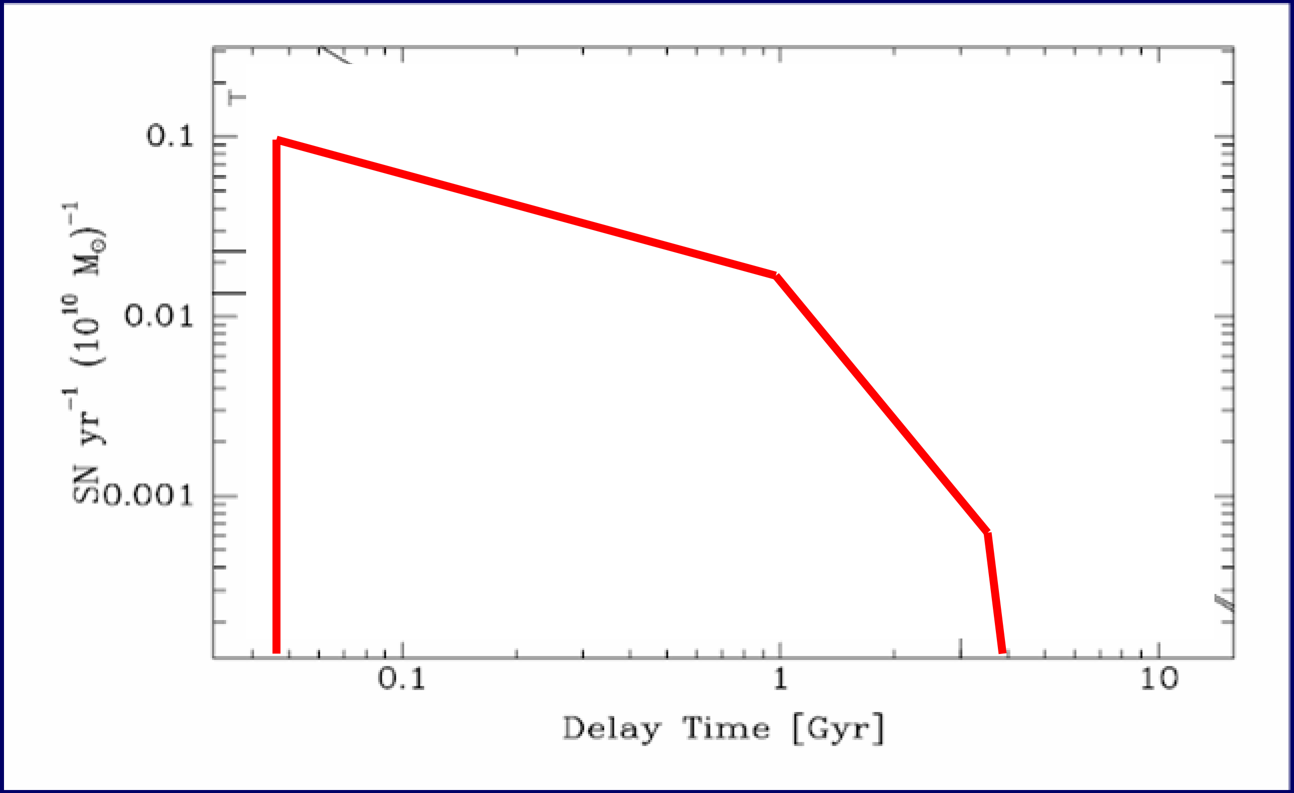
So DTD ~ t^{-1} expected generically

double-degenerate: DTD ~ t $^{-1}$ expected generically



similar reasoning:

single-degenerate: DTD ~ $t^{-0.5}$ + cutoff at few Gyr



How to recover the delay time distribution (5 different ways)

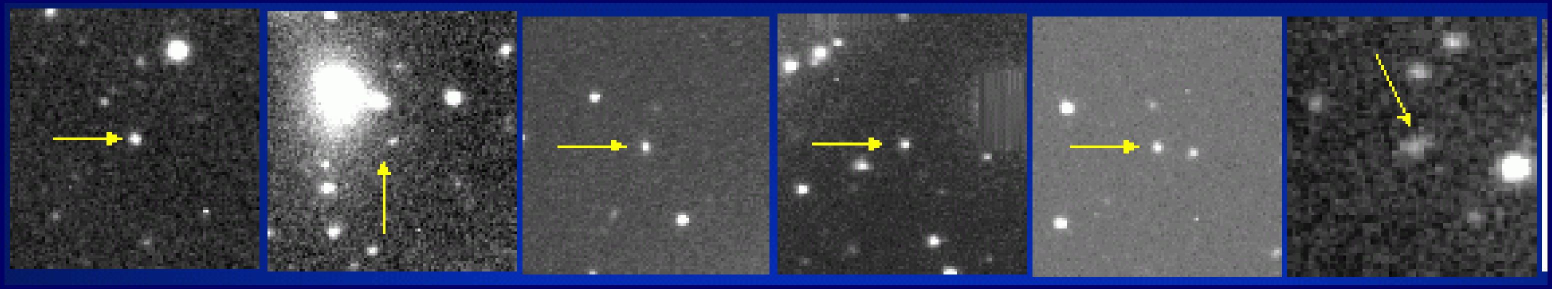
I. SN rates in galaxy clusters

Galaxy cluster SN rate measurements

z~0.1:

Wise Obs. 1m

Gal-Yam et al. (2008)
Sharon et al. (2007)

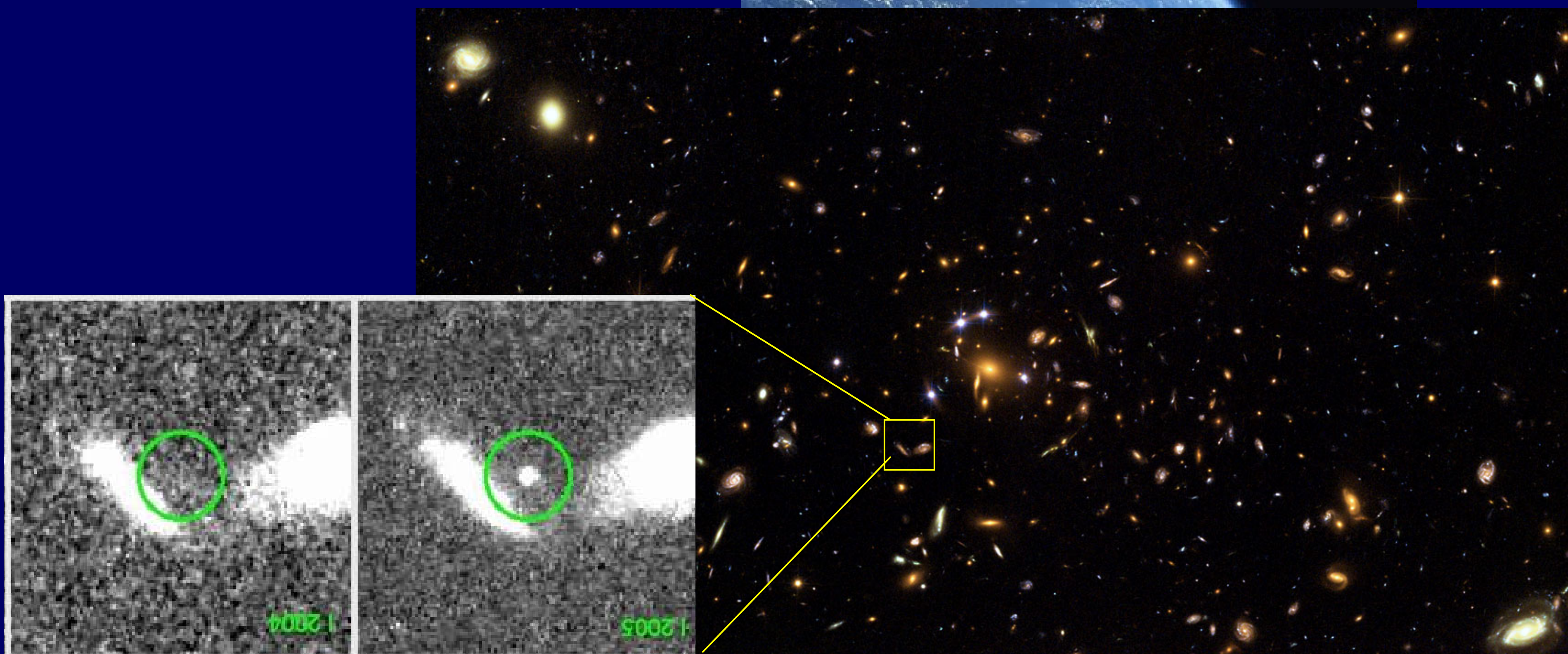


Galaxy cluster SN rate measurements

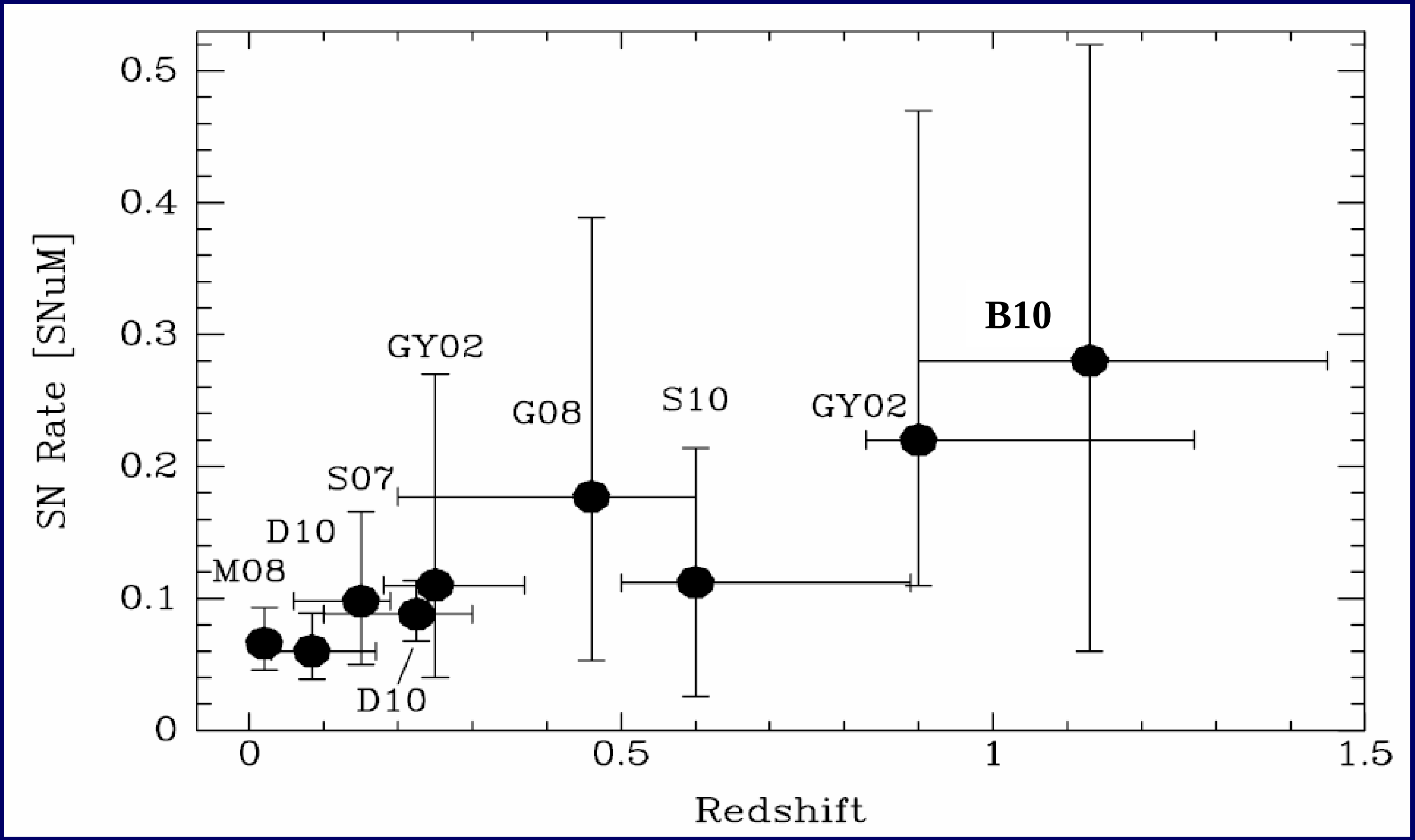
z~0.6:

HST (PI Gal-Yam)

Sharon et al. (2010)



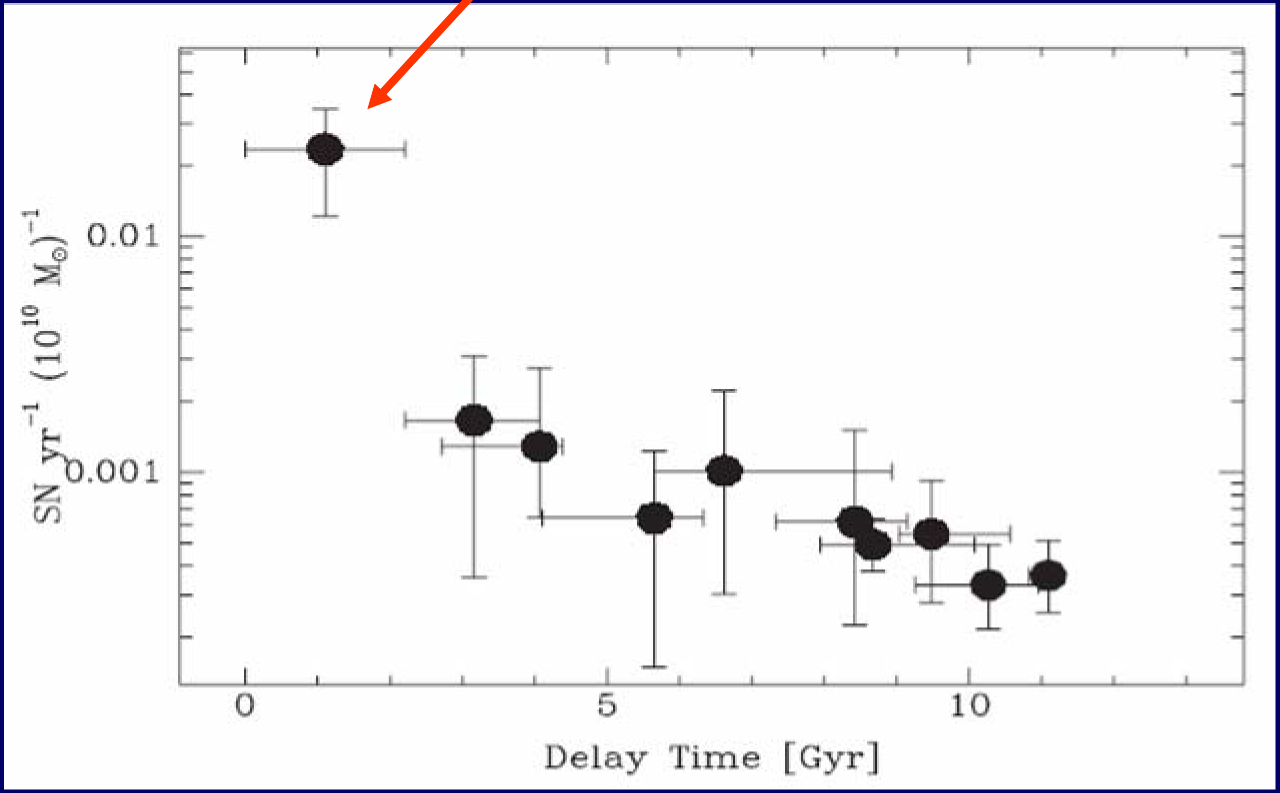
The SN rate vs. redshift in galaxy clusters



Cosmic time

Maoz, Sharon, Gal-Yam (2010)

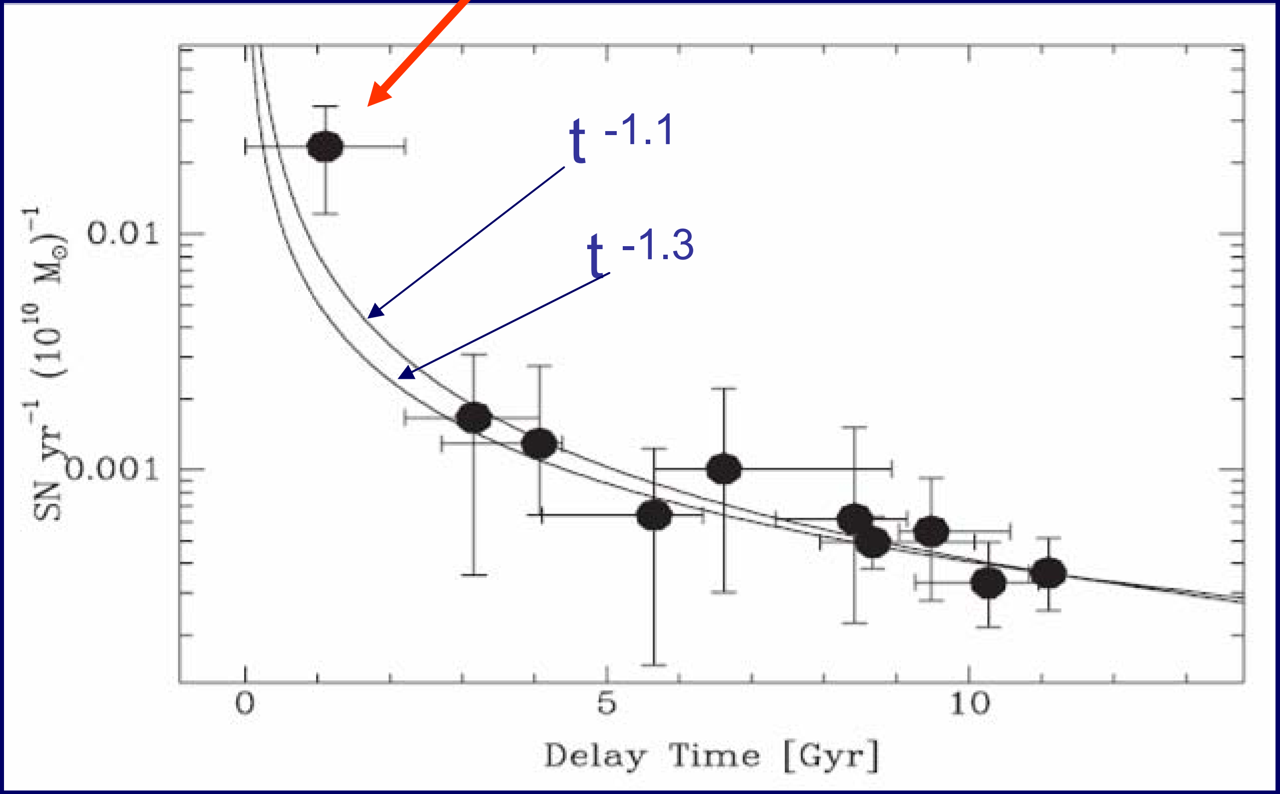
Time-integrated # of SNe-Ia must produce observed mass of Fe in clusters (minus mass from CC-SNe)



Maoz, Sharon, Gal-Yam (2010)

SN rates in galaxy clusters + iron/star mass ratio

Time-integrated # of SNe-Ia must produce observed mass of Fe in clusters



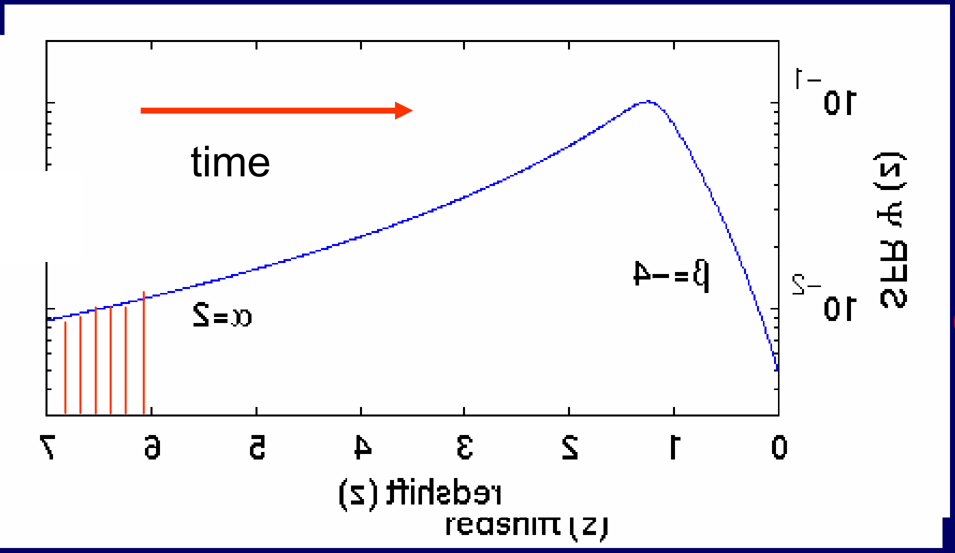
Maoz, Sharon, Gal-Yam (2010)

SN rates in galaxy clusters + iron/star mass ratio

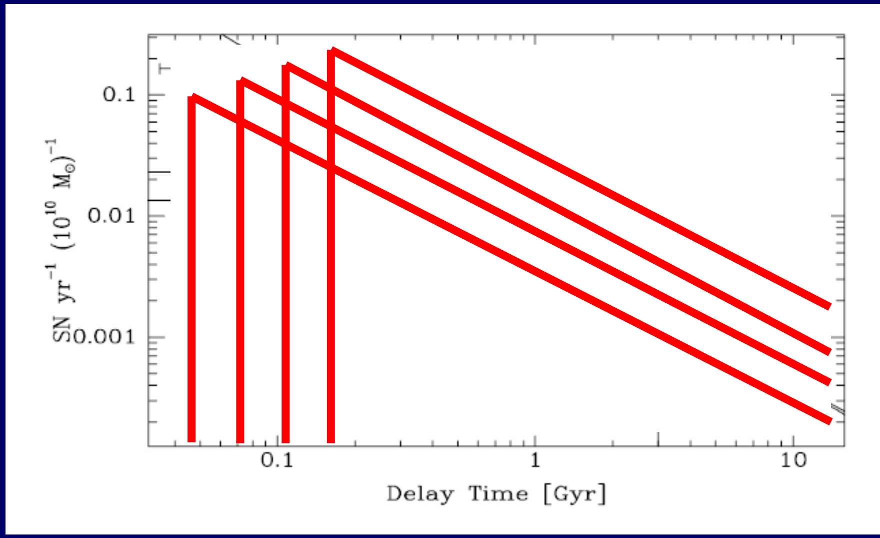
How to recover the delay time distribution

II. SN rates vs. redshift in field, compared to cosmic SFH

Star-formation history (z)

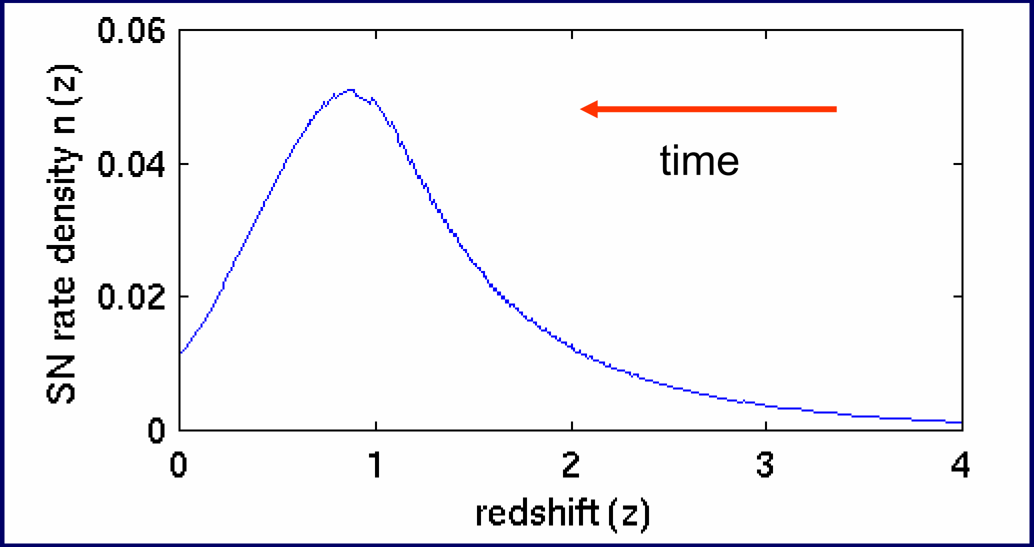


SN delay time distribution (t)



⊗

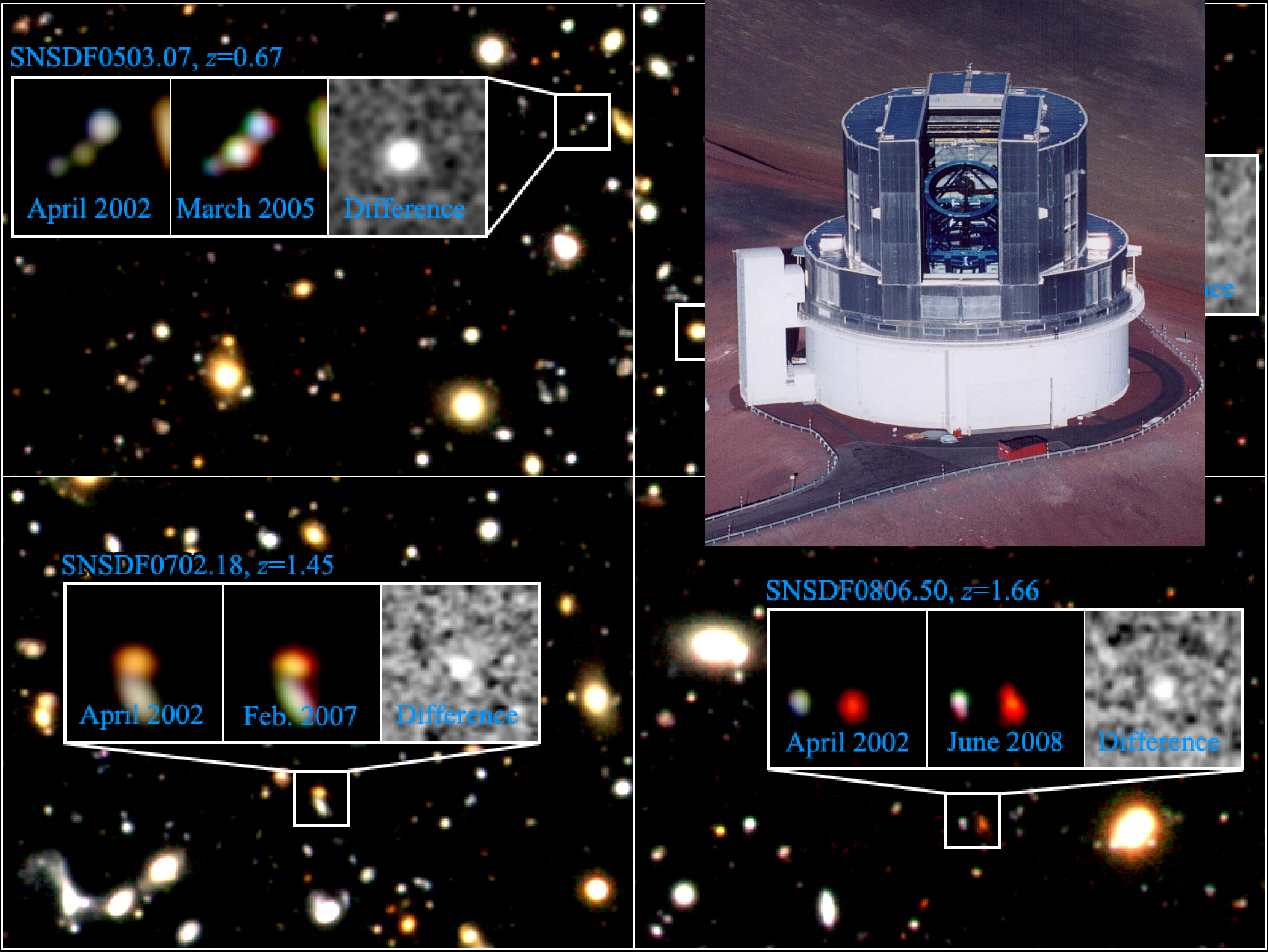
=



SN rate (z)

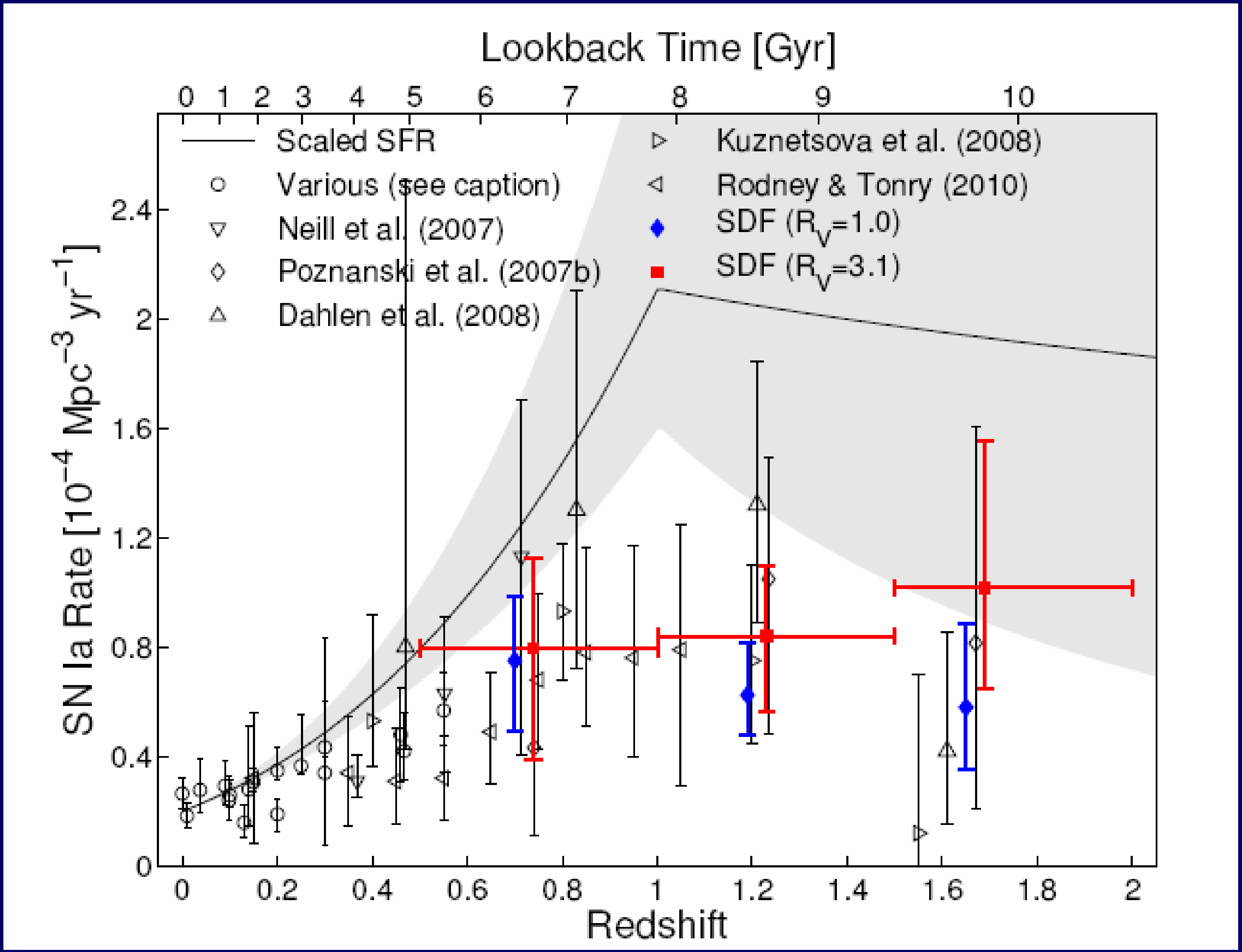
SN rate SFH delay time dist.

$$R_{\mathrm{Ia}}(t) = \int_0^t S(t-\tau)\Psi(\tau)d\tau.$$

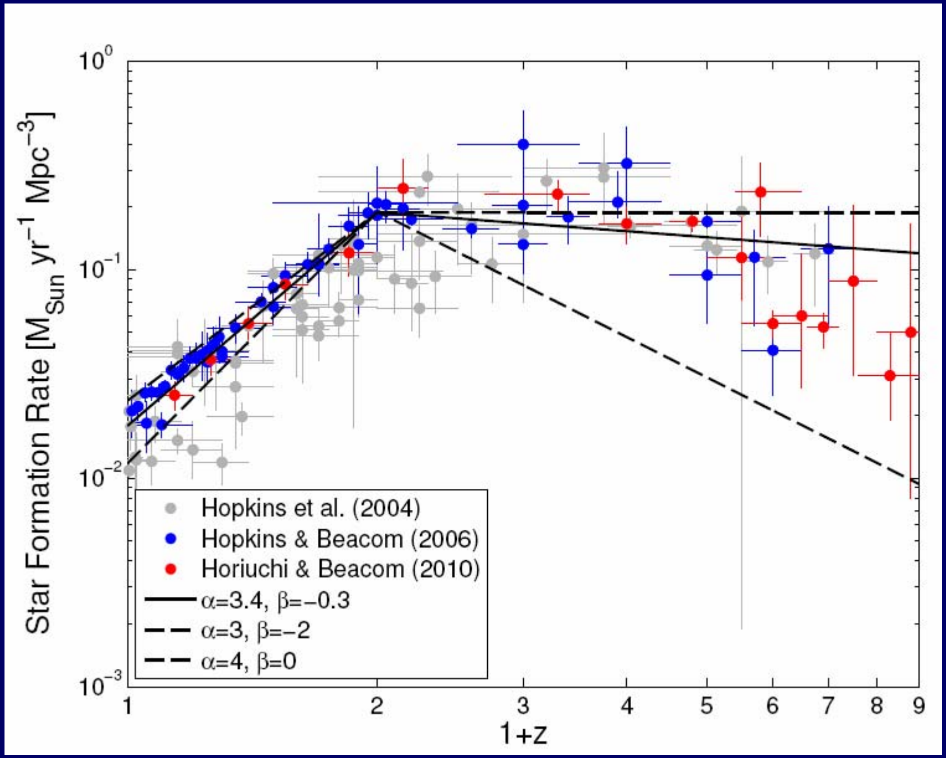

SNSDF0503.07, z=0.67
April 2002
March 2005
Difference
SNSDF0702.18, z=1.45
April 2002
Feb. 2007
Difference
SNSDF0806.50, z=1.66
April 2002
June 2008
Difference

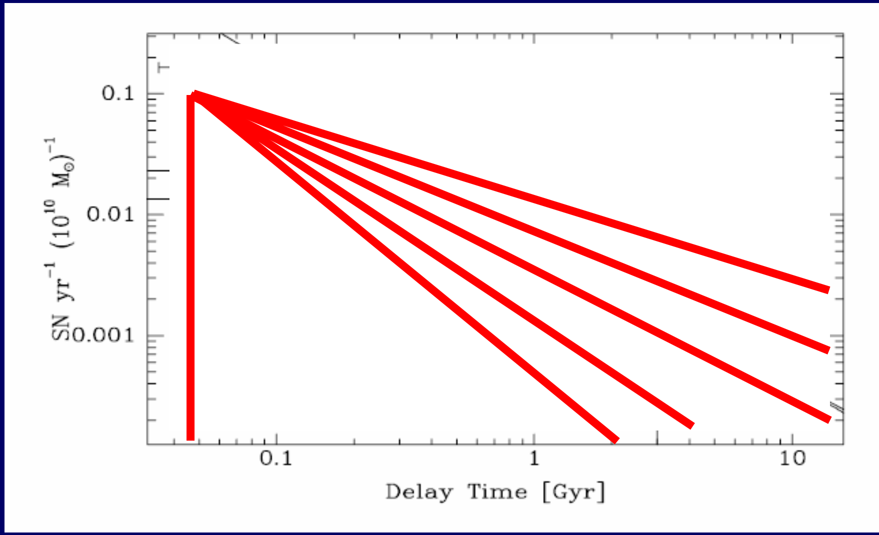
Subaru Deep Field Search (Poznanski+2007; Graur+2011)

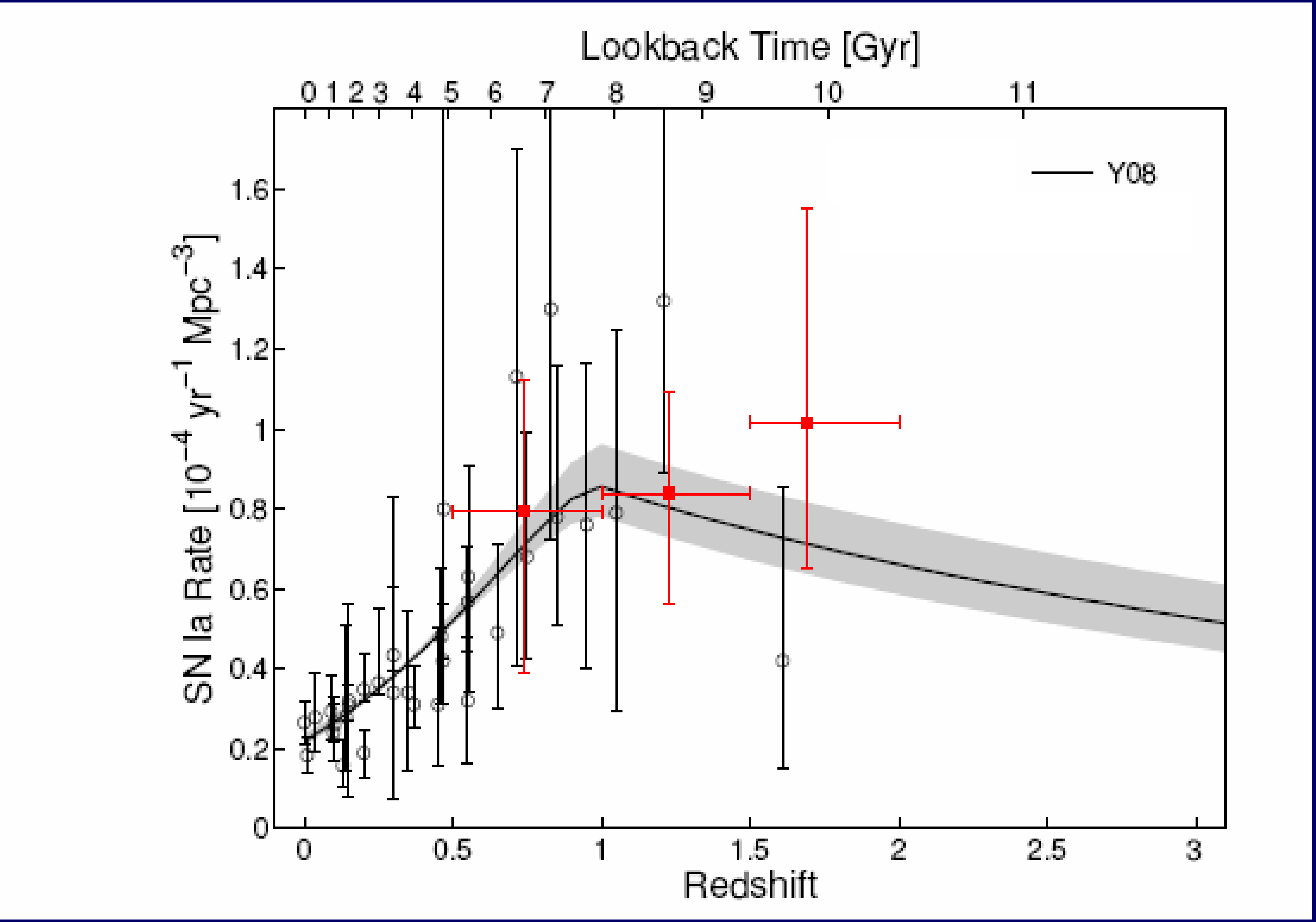
After 4 successful runs in 2005 - 2008: 150 SNe.

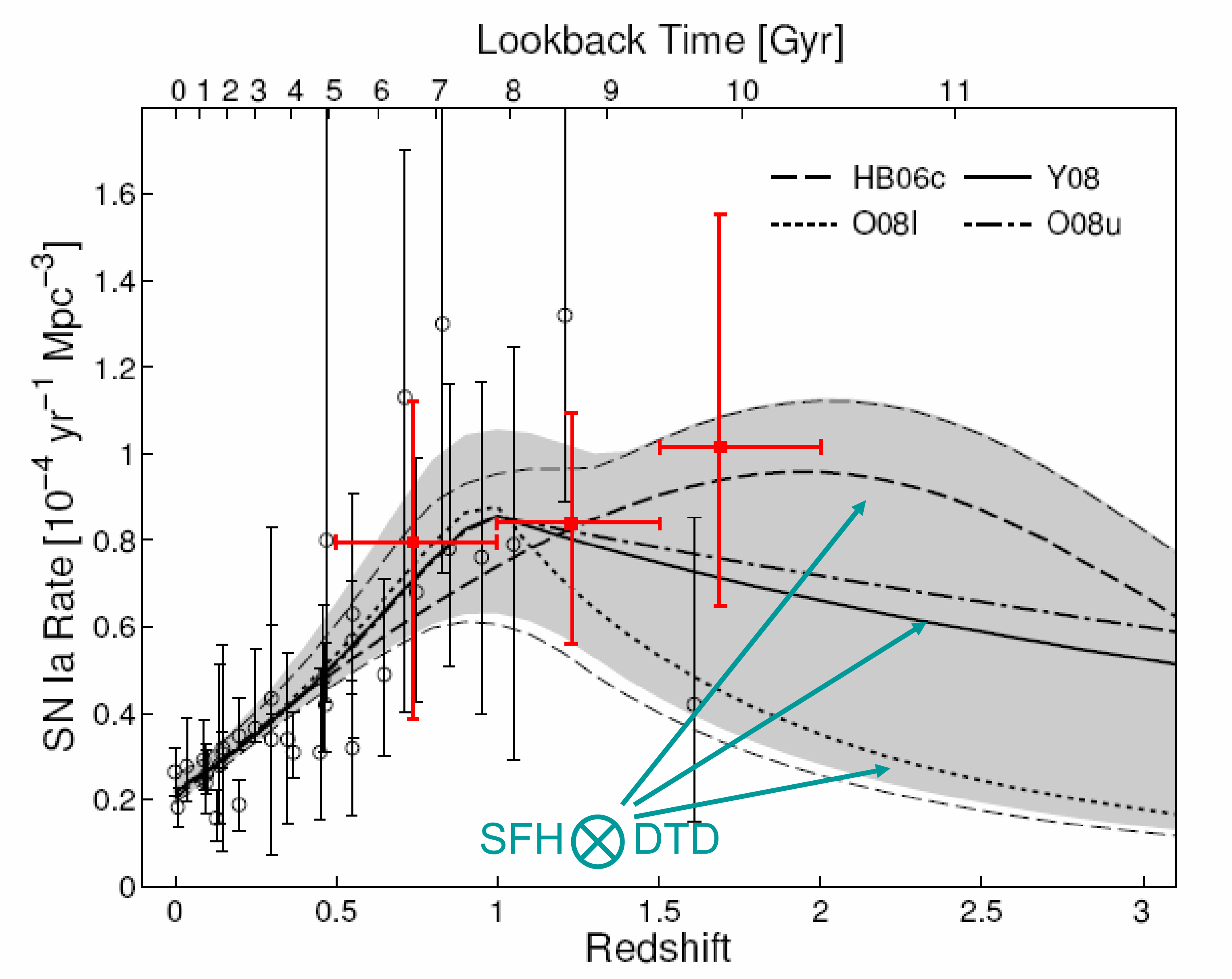


Star-formation history (z) ⊗ SN delay time distribution (t)



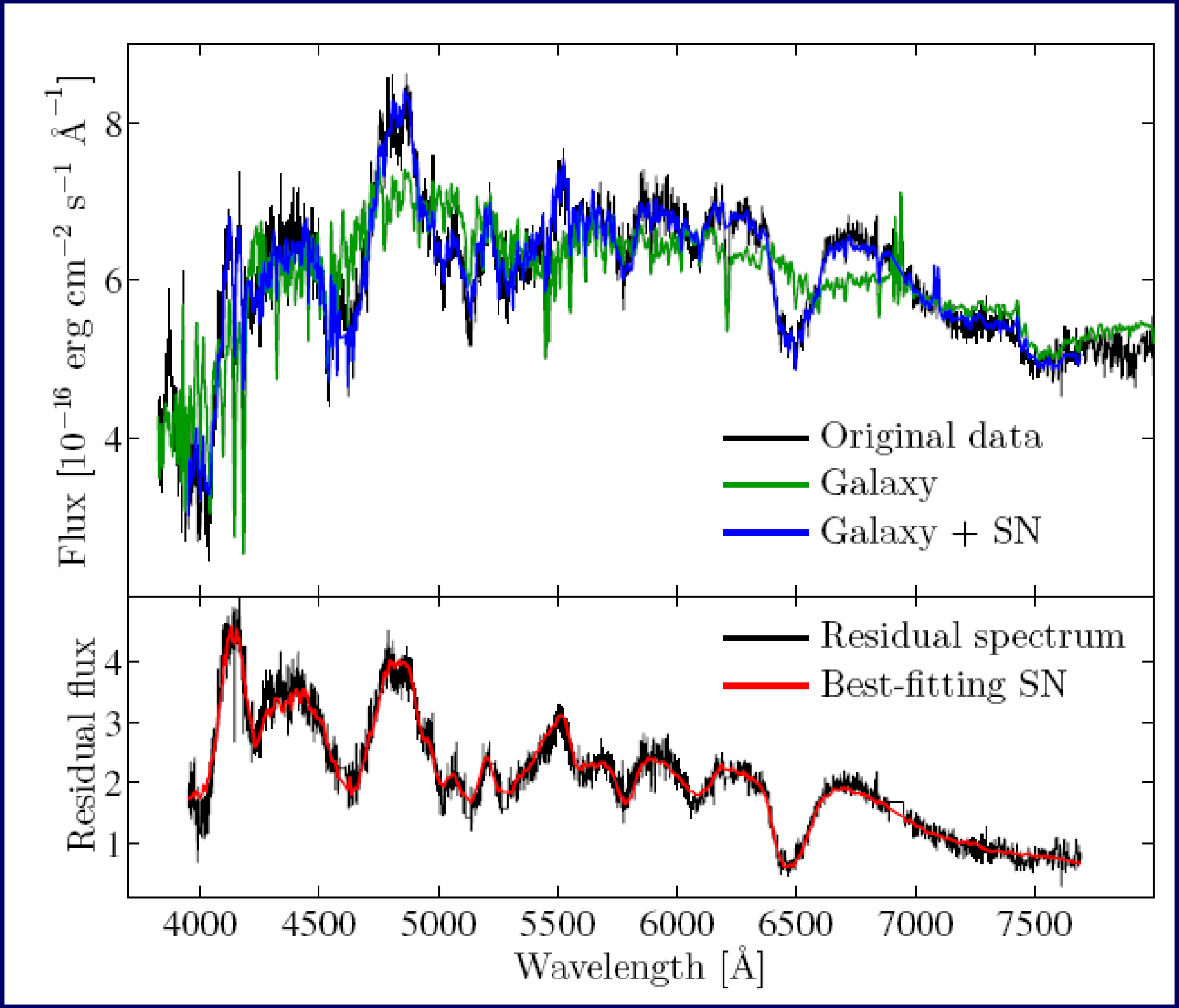



Lookback Time [Gyr]
0 1 2 3 4 5 6 7 8 9 10 11
Y08
SN Ia Rate [10^-4 yr^-1 Mpc^-3]
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6
0 0.5 1 1.5 2 2.5 3
Redshift

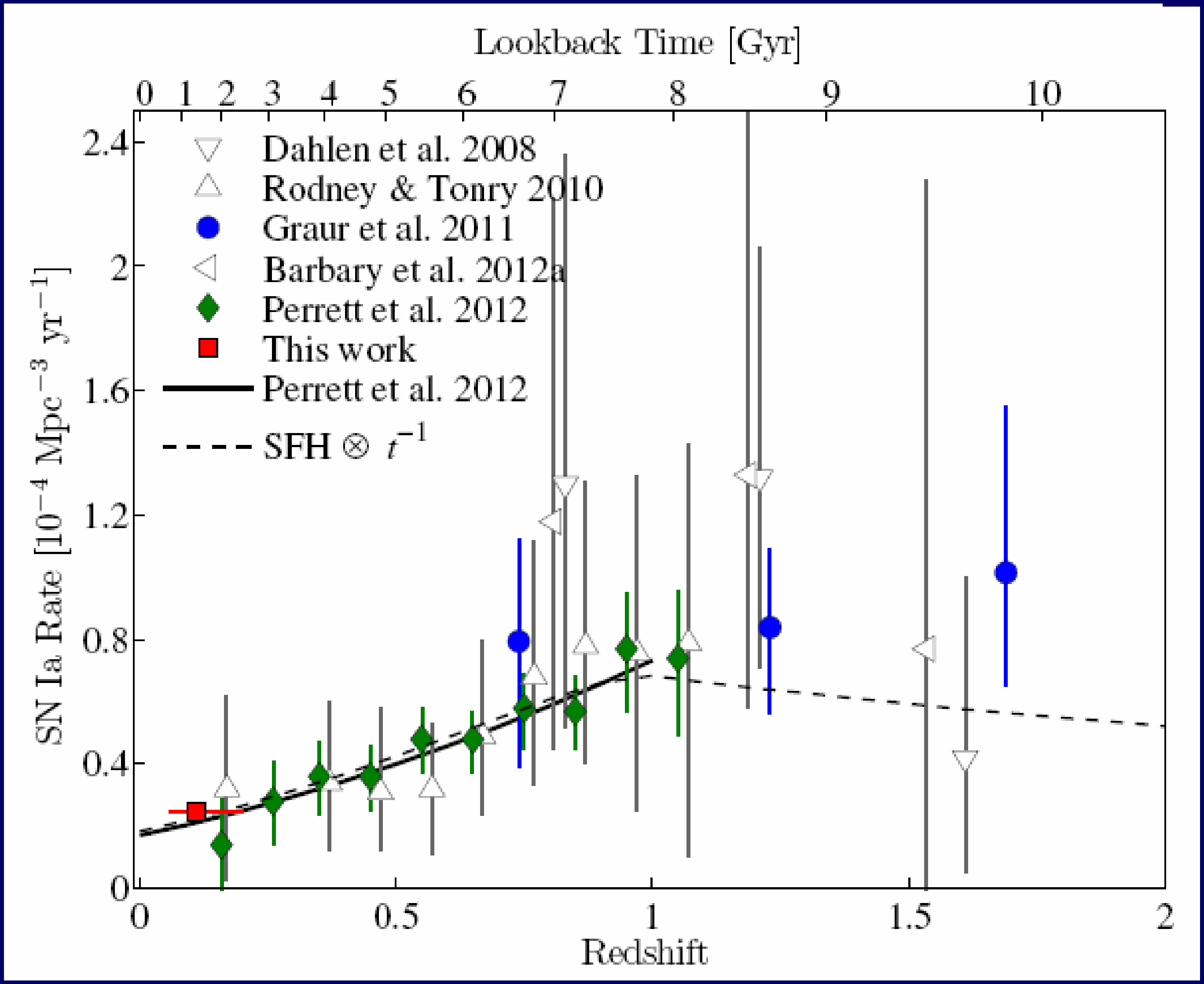


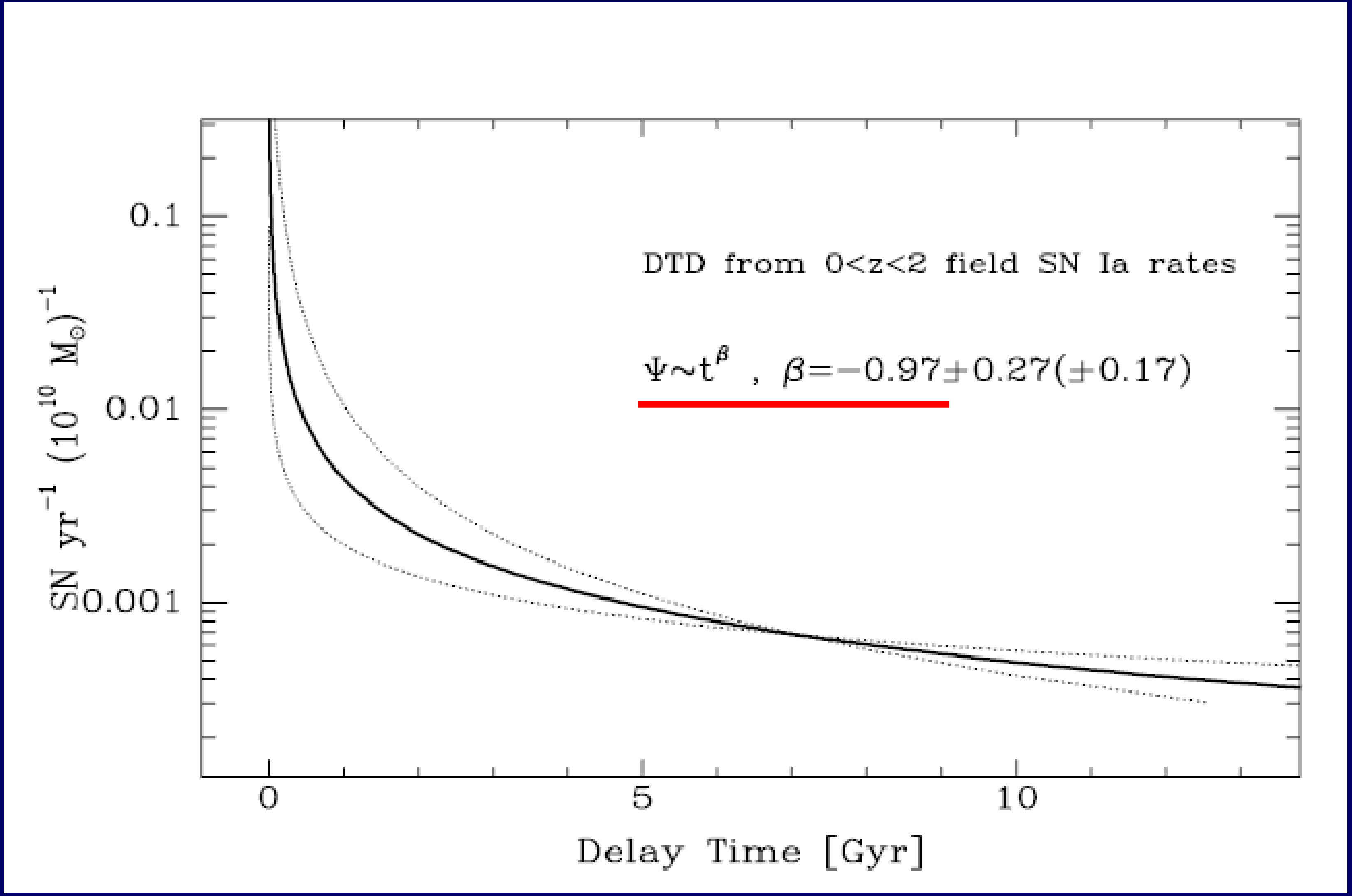
Lookback Time [Gyr]
0 1 2 3 4 5 6 7 8 9 10 11
HB06c
Y08
O08l
O08u
SN Ia Rate [10−4 yr−1 Mpc−3]
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6
0 0.5 1 1.5 2 2.5 3
Redshift
SFH ⊗ DTD

A SN survey among 700,000 SDSS spectra: 100 SNe (Graur & Maoz 12; see poster)



Graur & Maoz 12

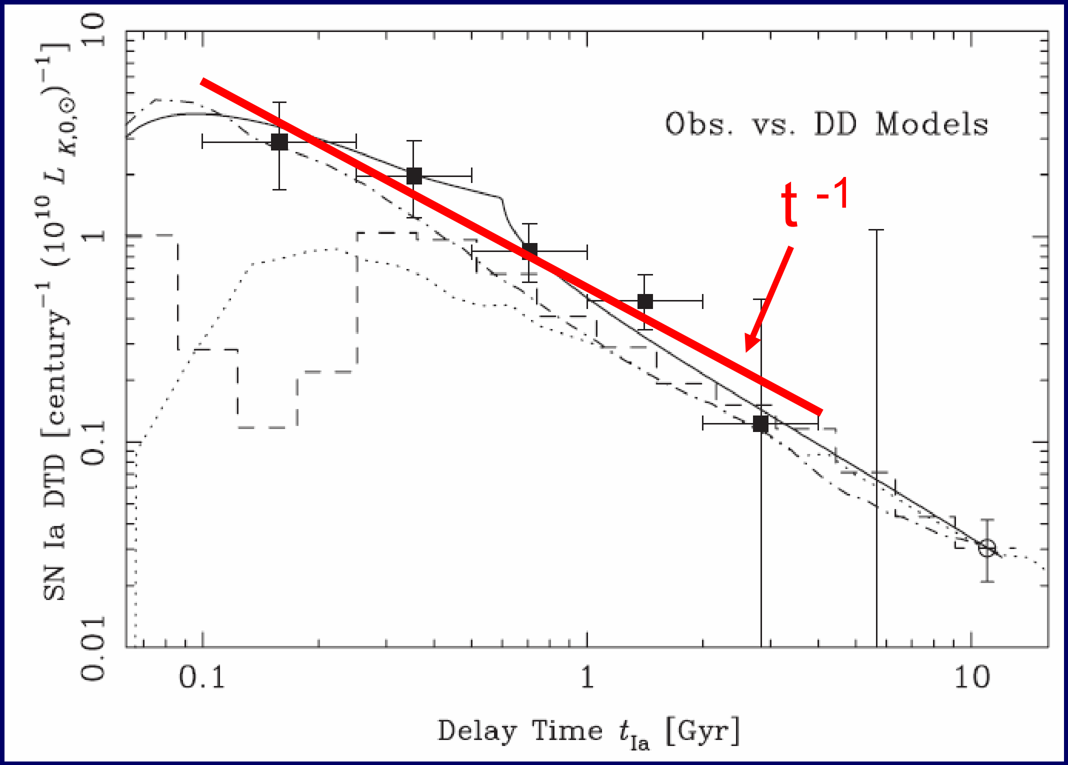




DTD from 0<z<2 field SN Ia rates
Ψ~t^β , β=−0.97±0.27(±0.17)
0.1
0.01
0.001
SN yr^-1 (10^10 M☉)^-1
0
5
10
Delay Time [Gyr]

How to recover the delay time distribution

III. SN Rates vs. galaxy “age”



Totani et al. 2008

SN rates in E galaxies at z=0.4-1.2

How to recover the delay time distribution

IV. SN Rates vs. individual galaxy star-formation histories

SN rate — SFH — delay function

$$r(t) = \int_0^{t_0} S(t-\tau)\Psi(\tau)d\tau,$$

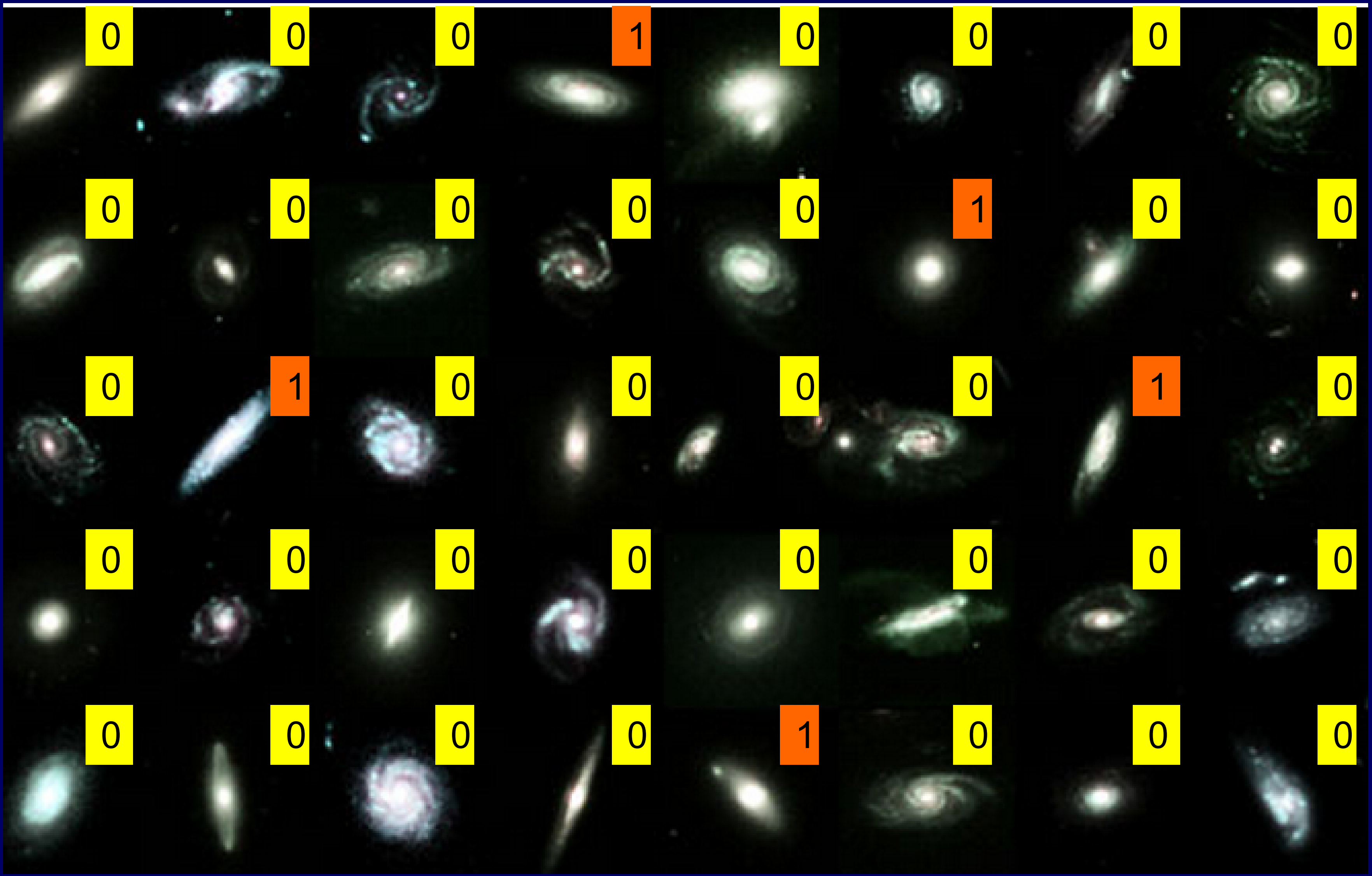
$$r = \sum_{j=1}^{K} m_j \Psi_j,$$

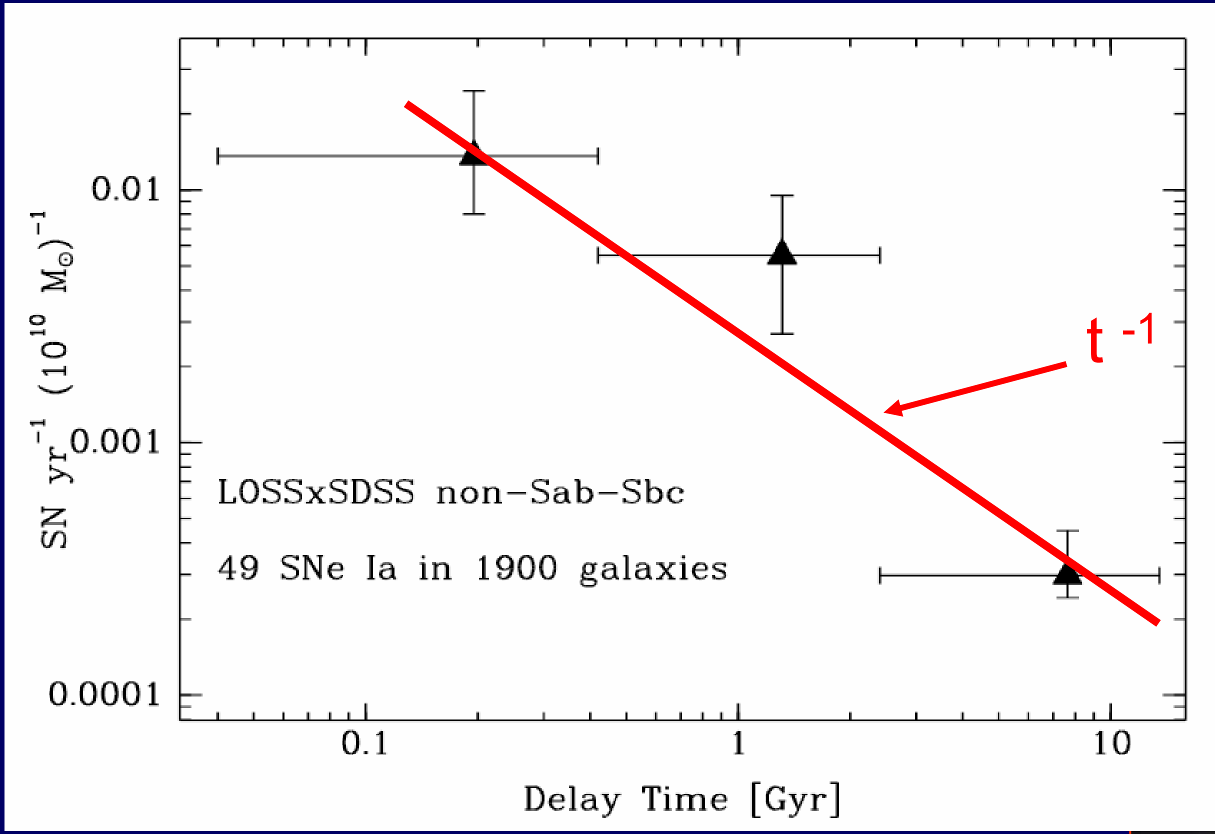
expec. value for # SNe in given galaxy

N = r • t

visibility time

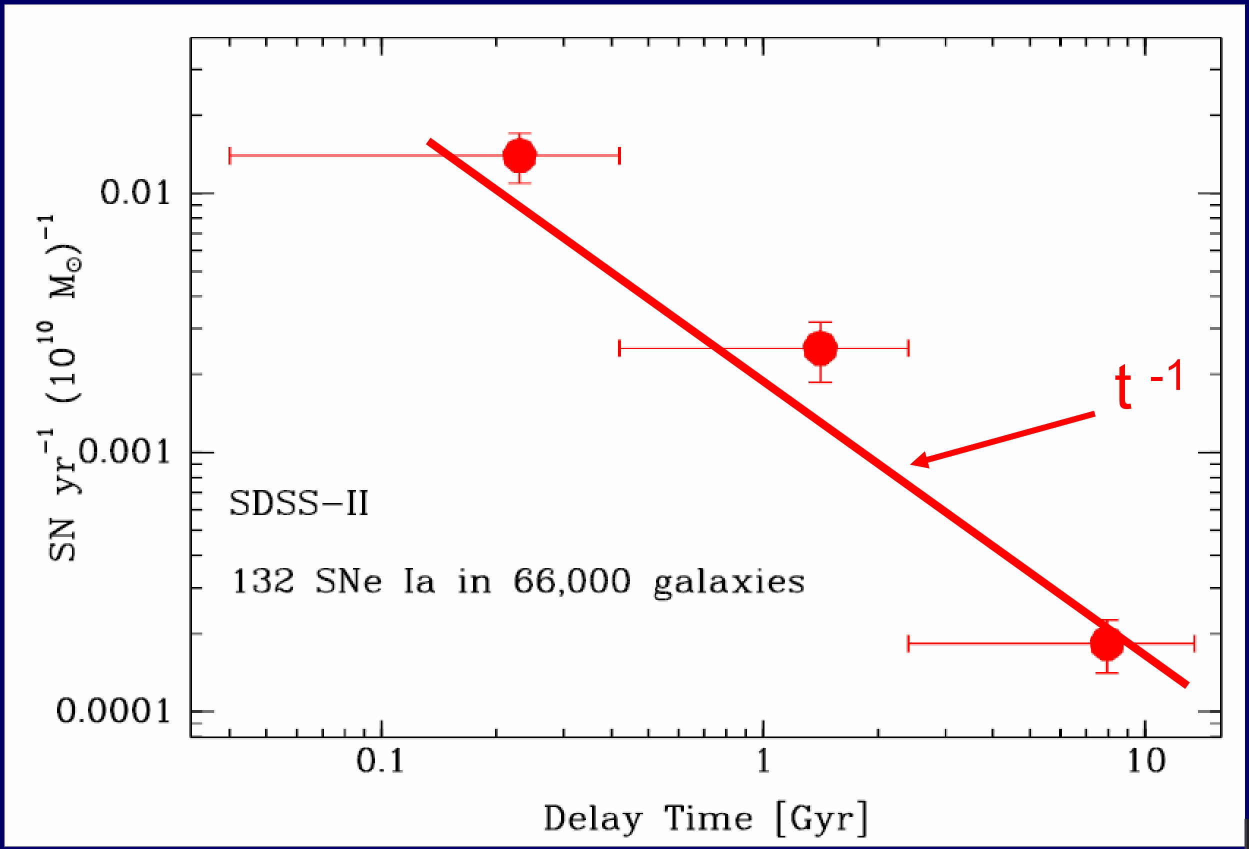
Compare observed number of SNe (0 or 1) in each galaxy to expectation value for given model DTD





Maoz, Mannucci, et al. 2011

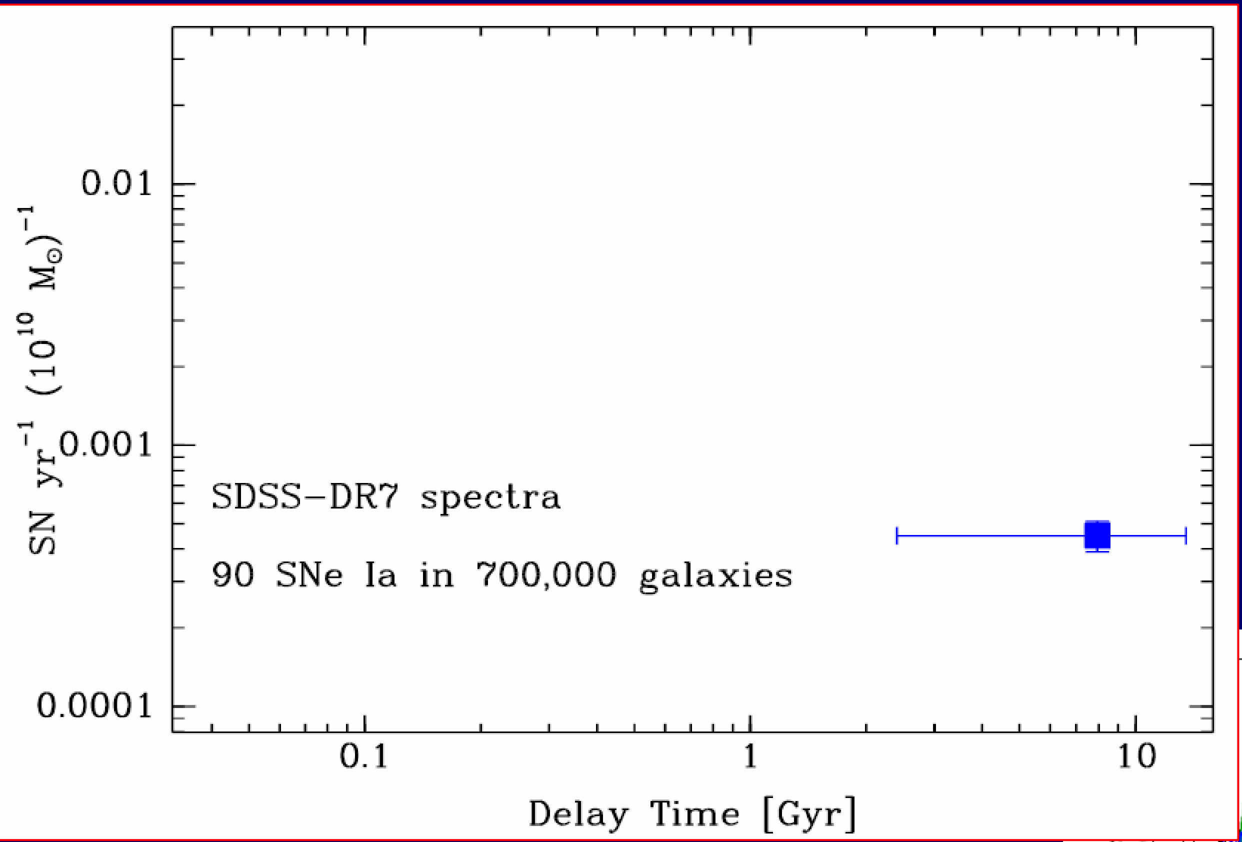
SNe from Lick Observatory SN Search (Filippenko, Li) in nearby galaxies, with SDSS spectra and SFH reconstructions (Tojeiro+09)

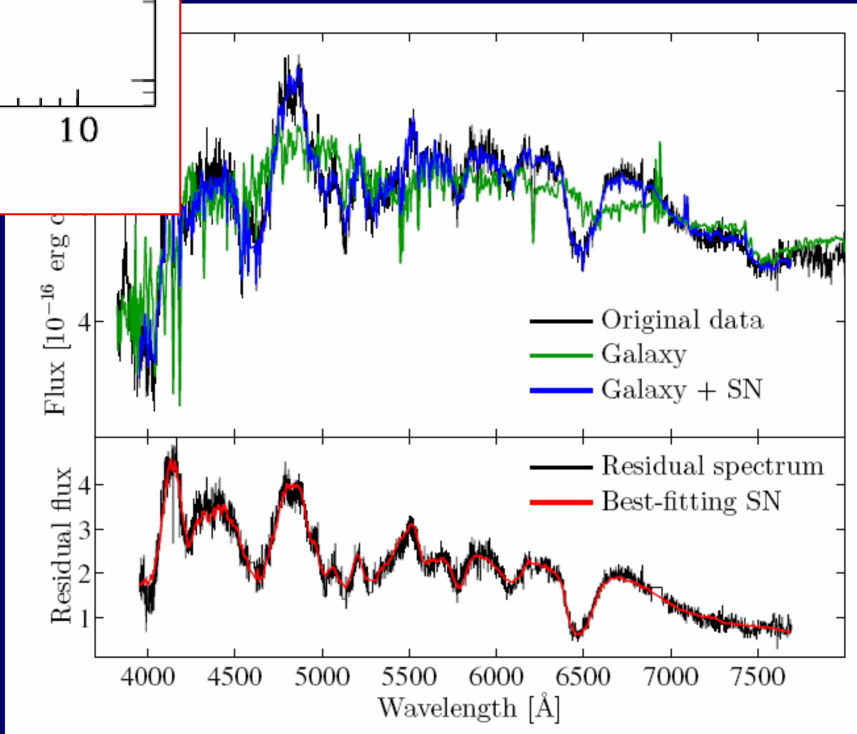


Maoz, Brandt, Mannucci 2012

SDSS-II SNe Ia in Stripe 82 galaxies with SDSS spectra and SFHs

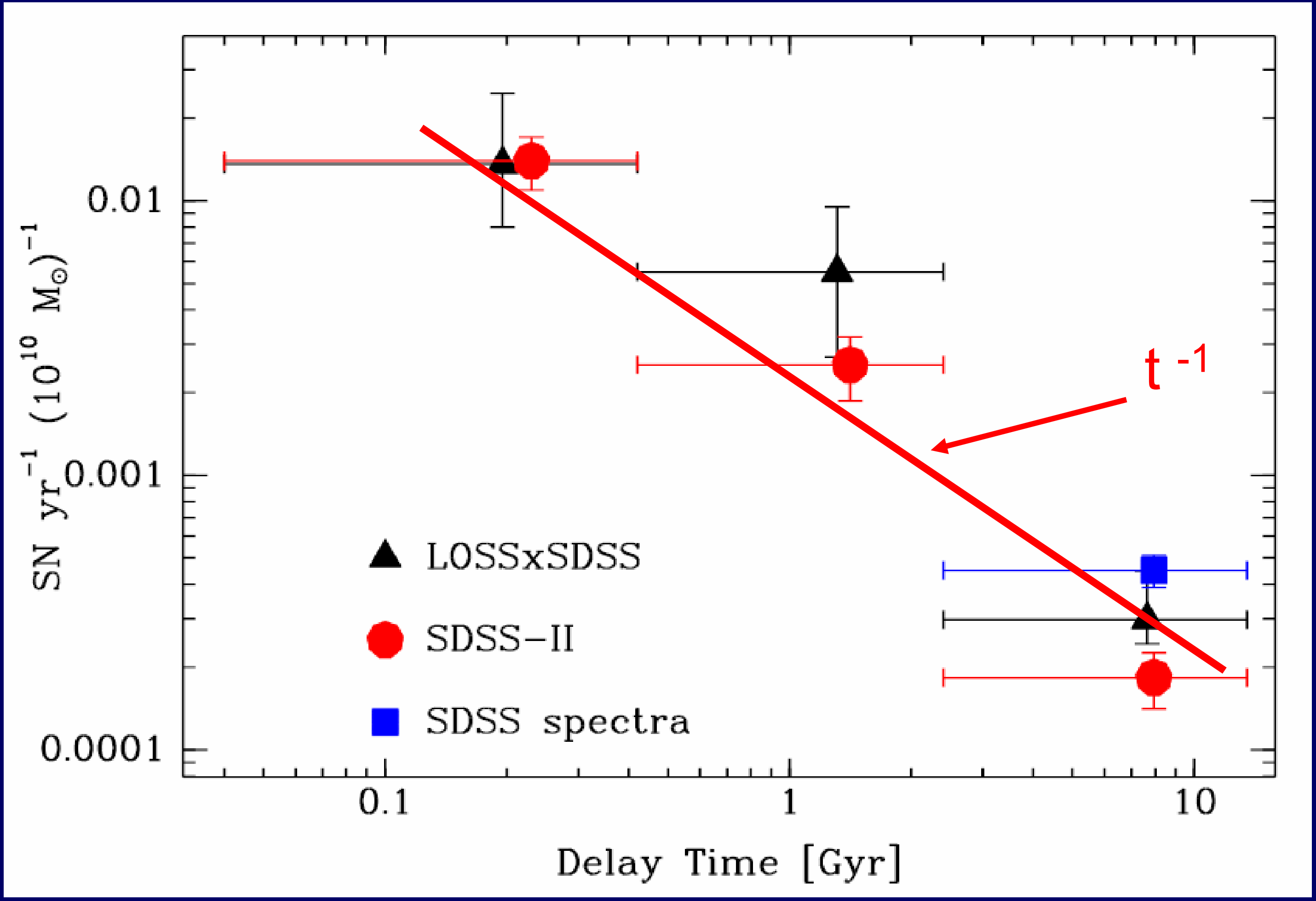
(also Brandt+10)





Graur & Maoz 2012

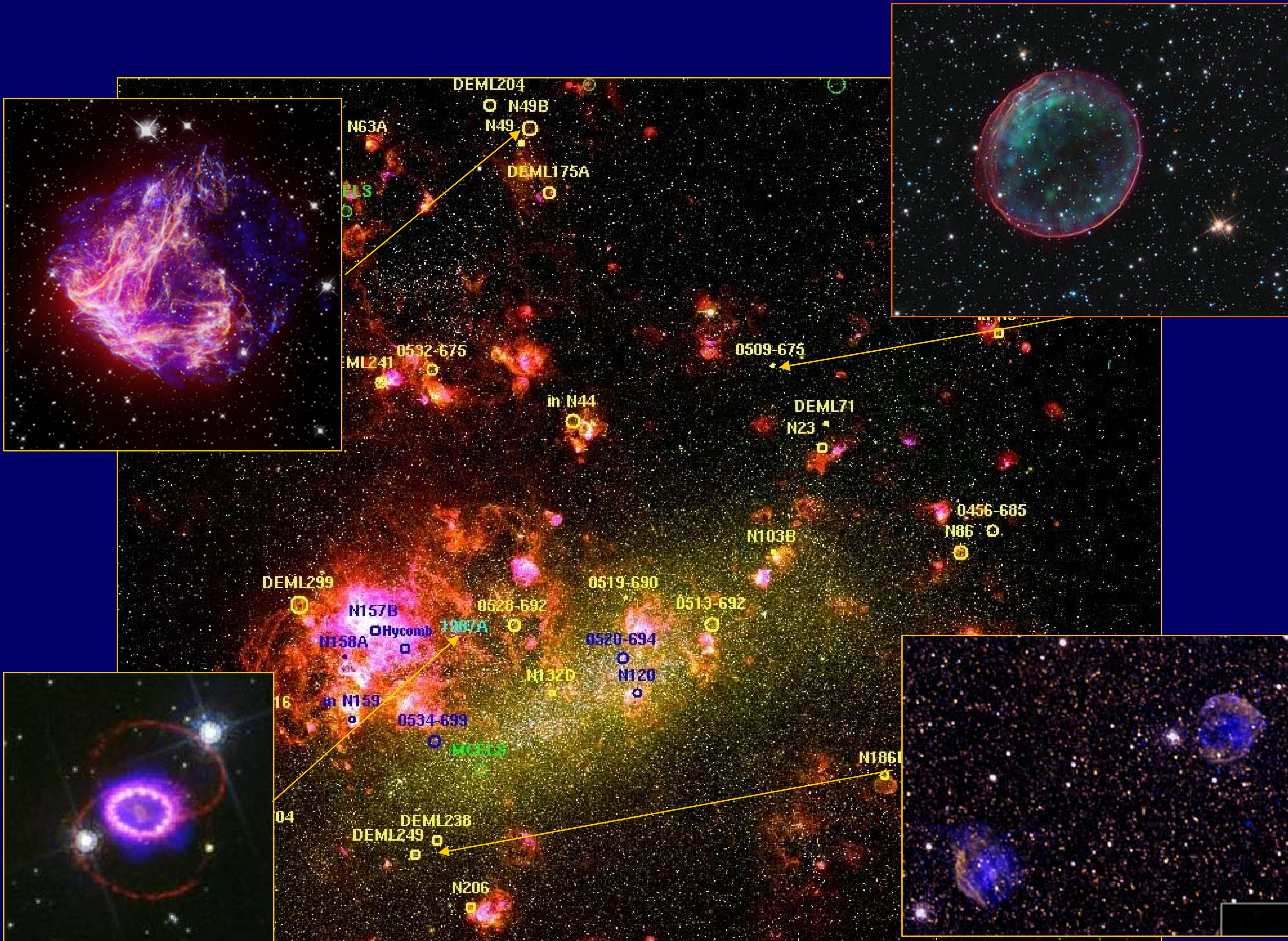
SNe Ia in SDSS DR7 spectra



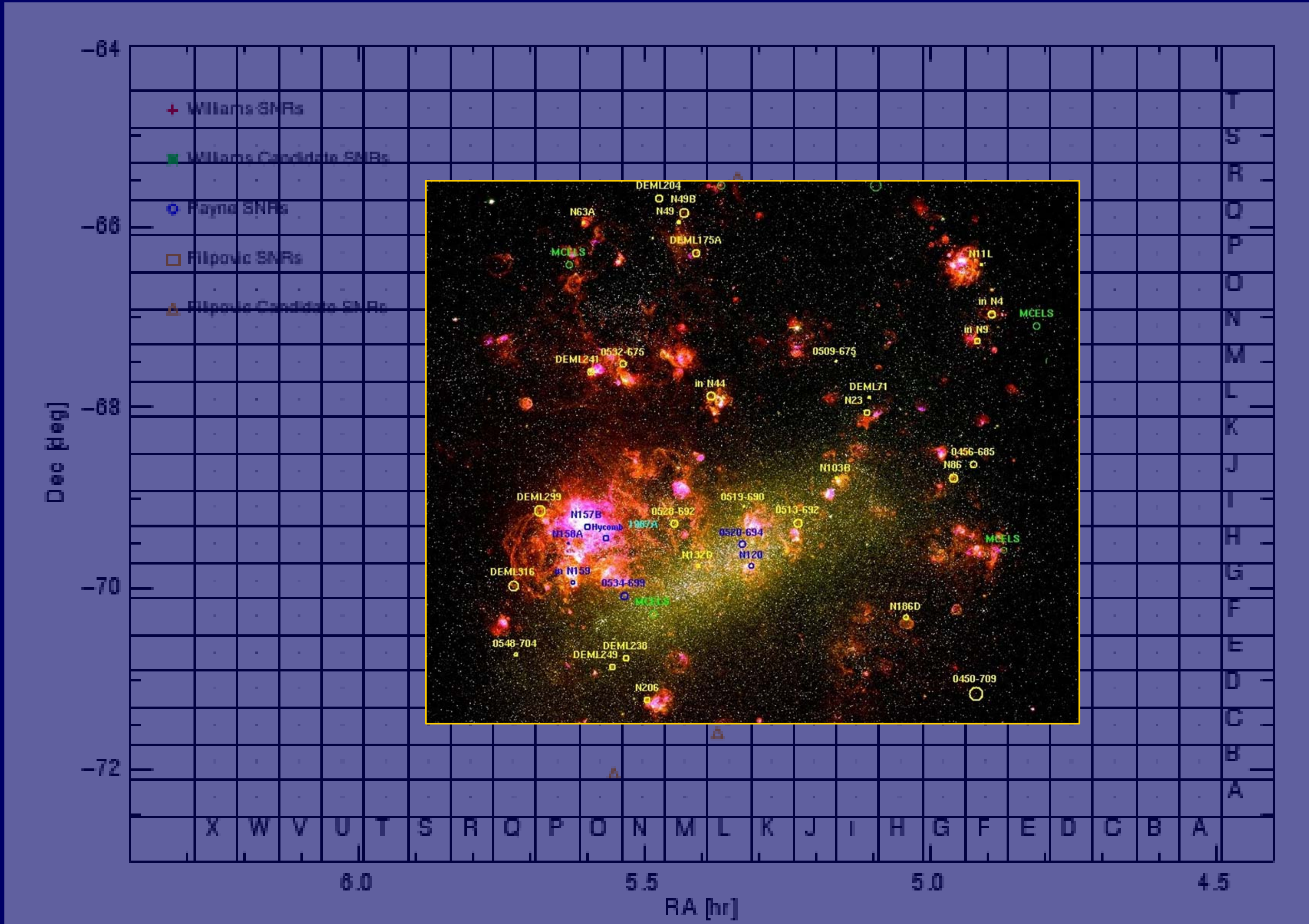
t -1
LOSSxSDSS
SDSS-II
SDSS spectra
0.01
0.001
0.0001
0.1
1
10
Delay Time [Gyr]
SN yr^{-1} (10^{10} $M_\odot$)$^{-1}$

How to recover the delay time distribution

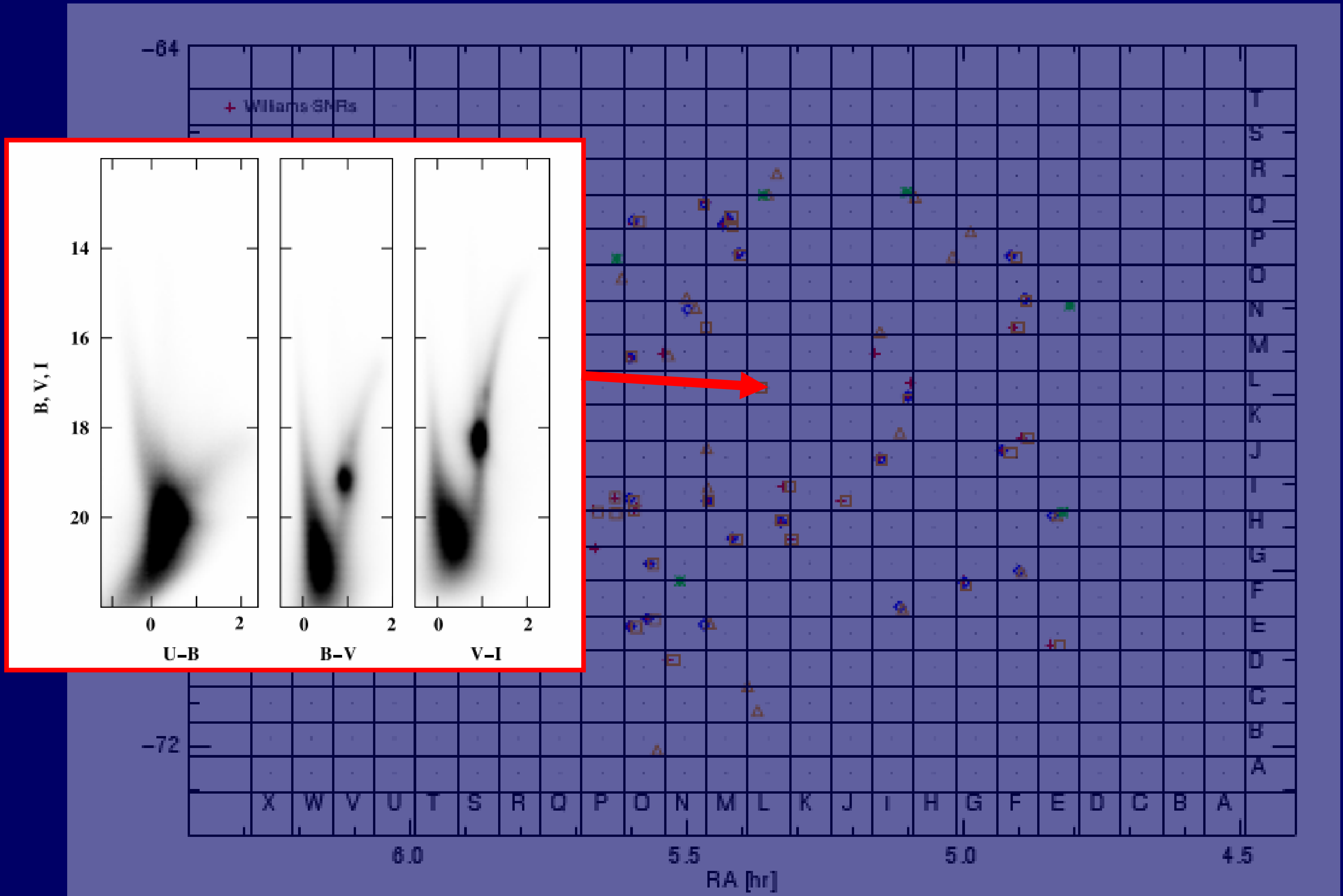
V. SN remnants in the LMC+SMC, viewed as a SN survey


DEML204
N49B
N63A
N49
DEML175A
0532-675
in N44
0509-675
DEML71
N23
0456-685
N86
N103B
DEML299
N157B
Hycomb
1987A
0528-692
0519-690
0513-692
N158A
0520-694
N132D
N120
in N159
0534-699
MCELS
DEML238
DEML249
N206

Star-formation histories in 1836 individual LMC/SMC "cells", from resolved stellar populations.
Harris & Zaritzky 2004, 2009

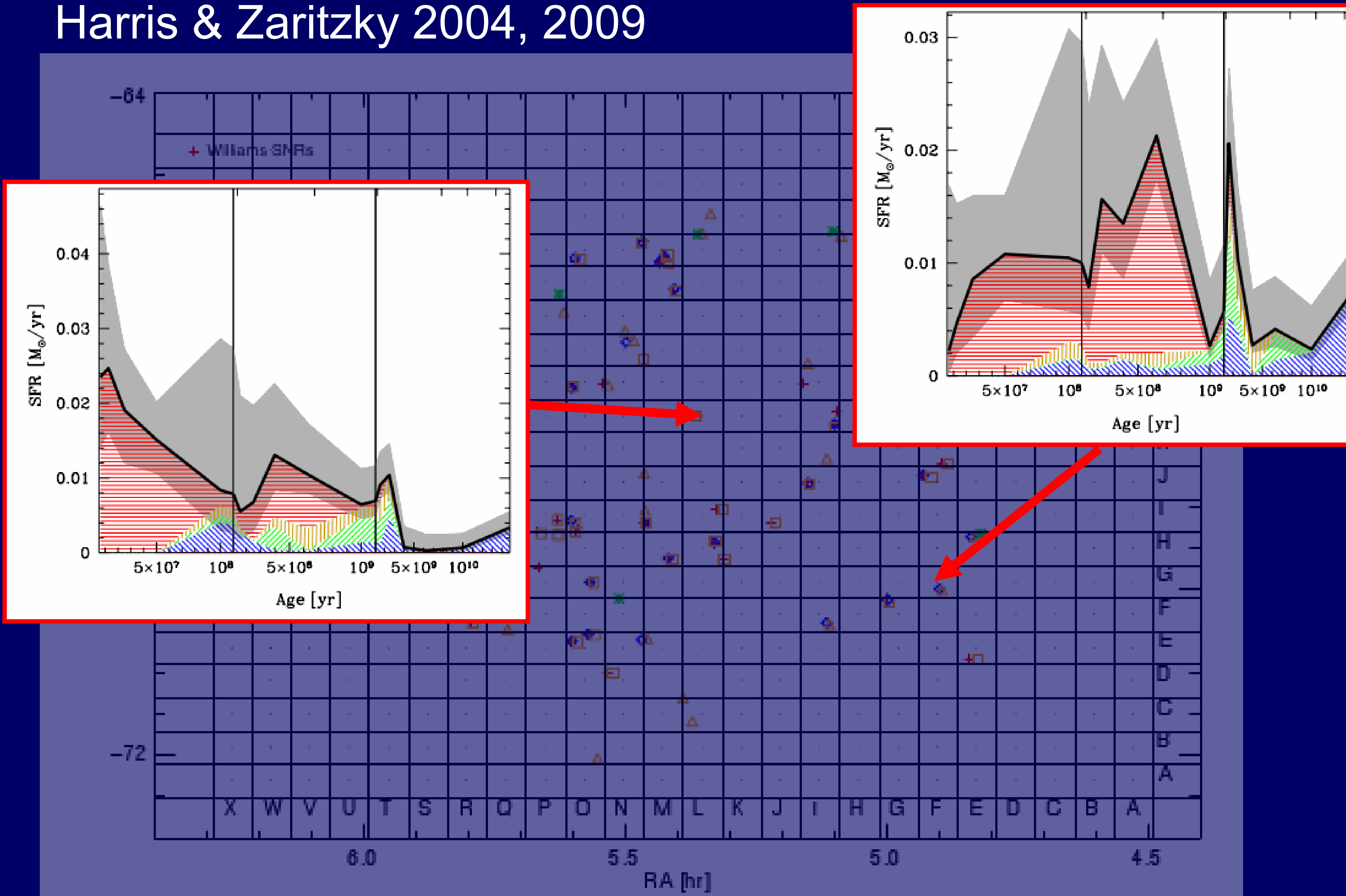


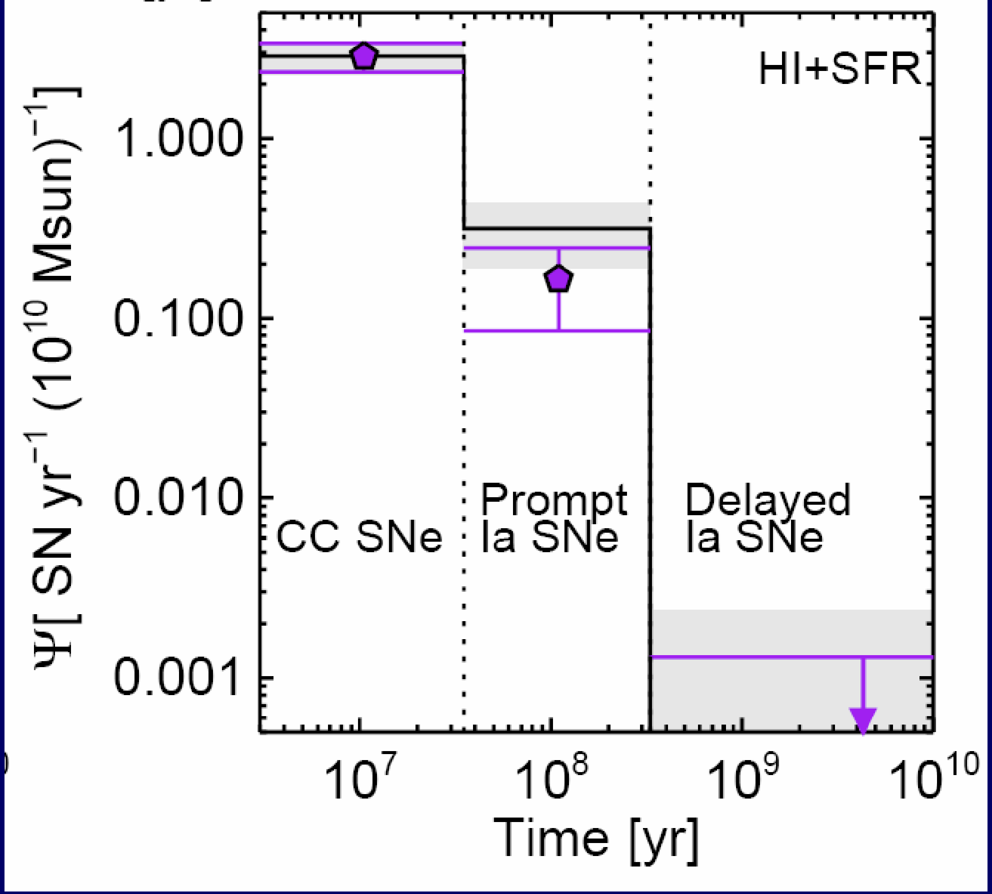
Star-formation histories in 1836 individual LMC/SMC "cells", from resolved stellar populations.
Harris & Zaritzky 2004, 2009



Star-formation histories in 1836 individual LMC/SMC “cells”, from resolved stellar populations.

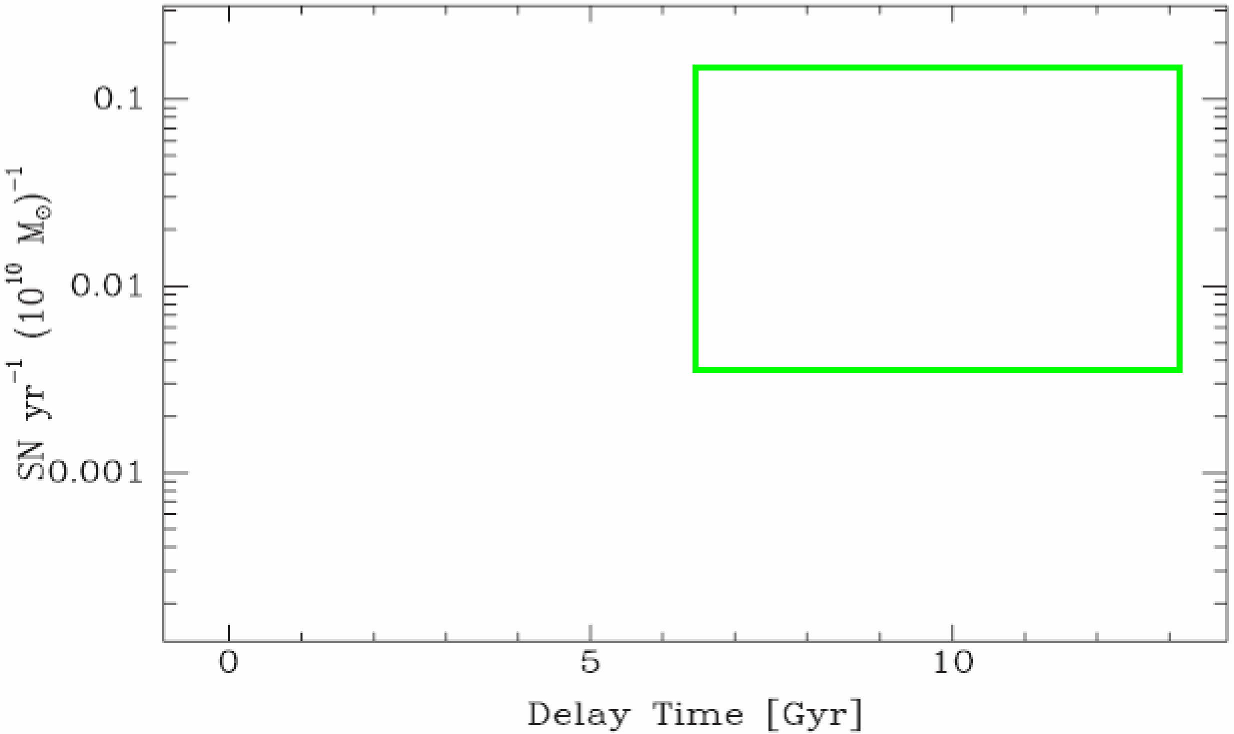
Harris & Zaritzky 2004, 2009



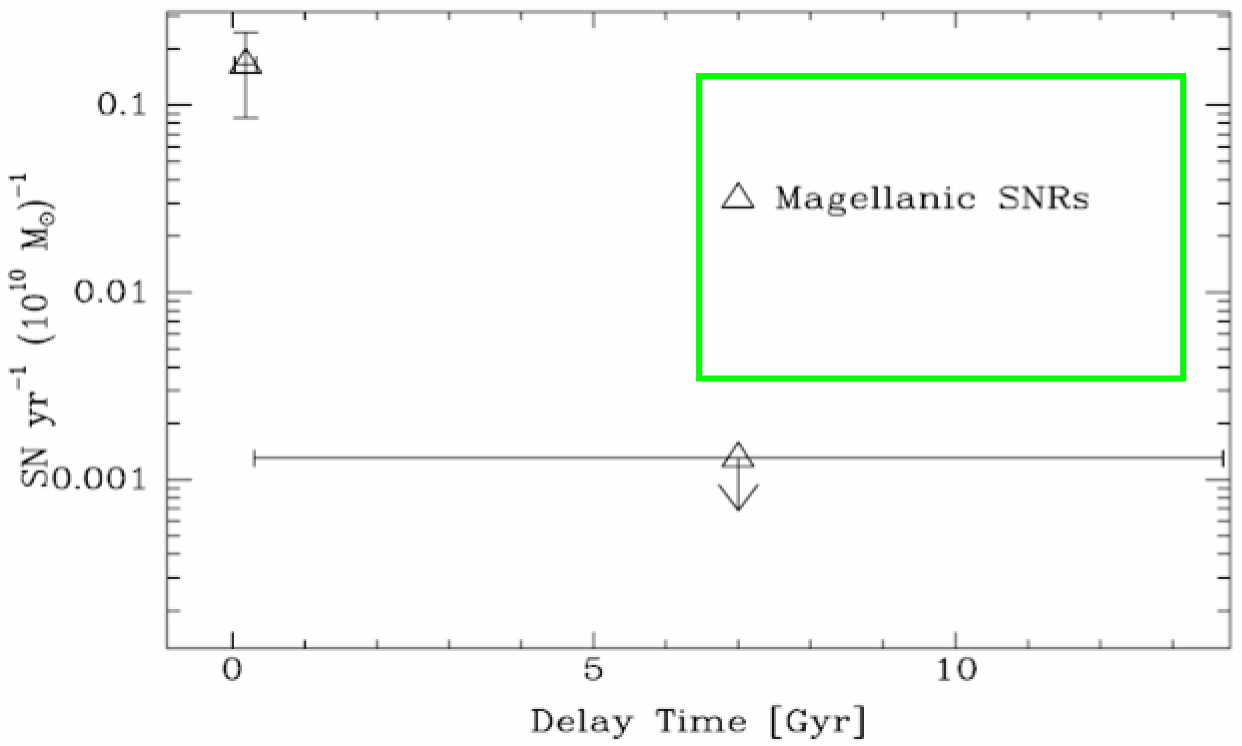


Maoz & Badenes 2010

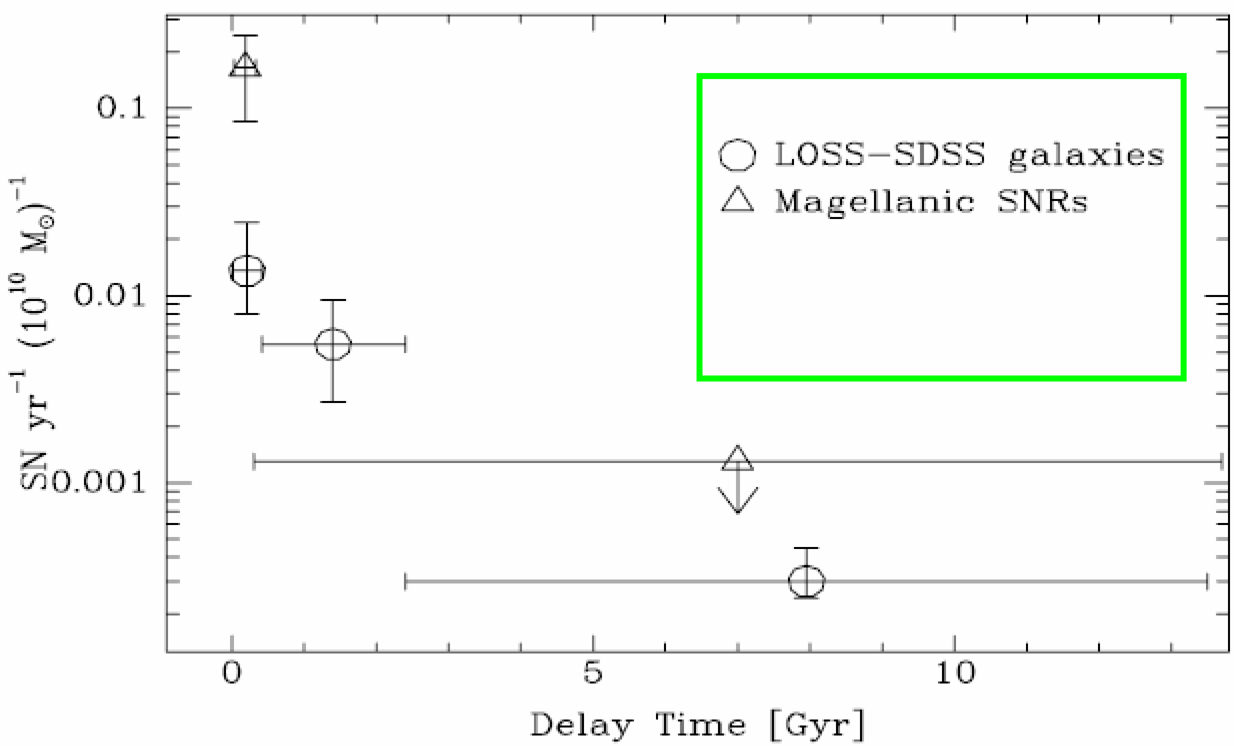
SN remnants in the Magellanic Clouds and SFHs from resolved stellar populations



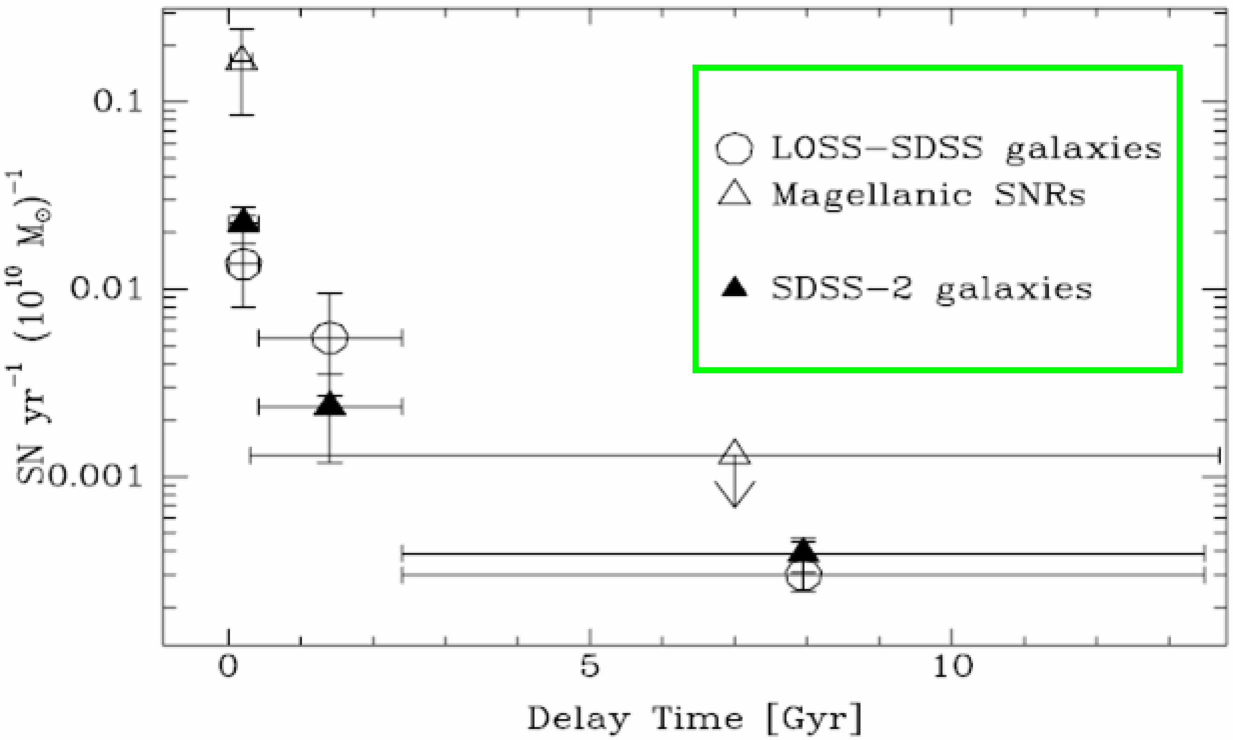
The DTD: a consistent picture emerging.



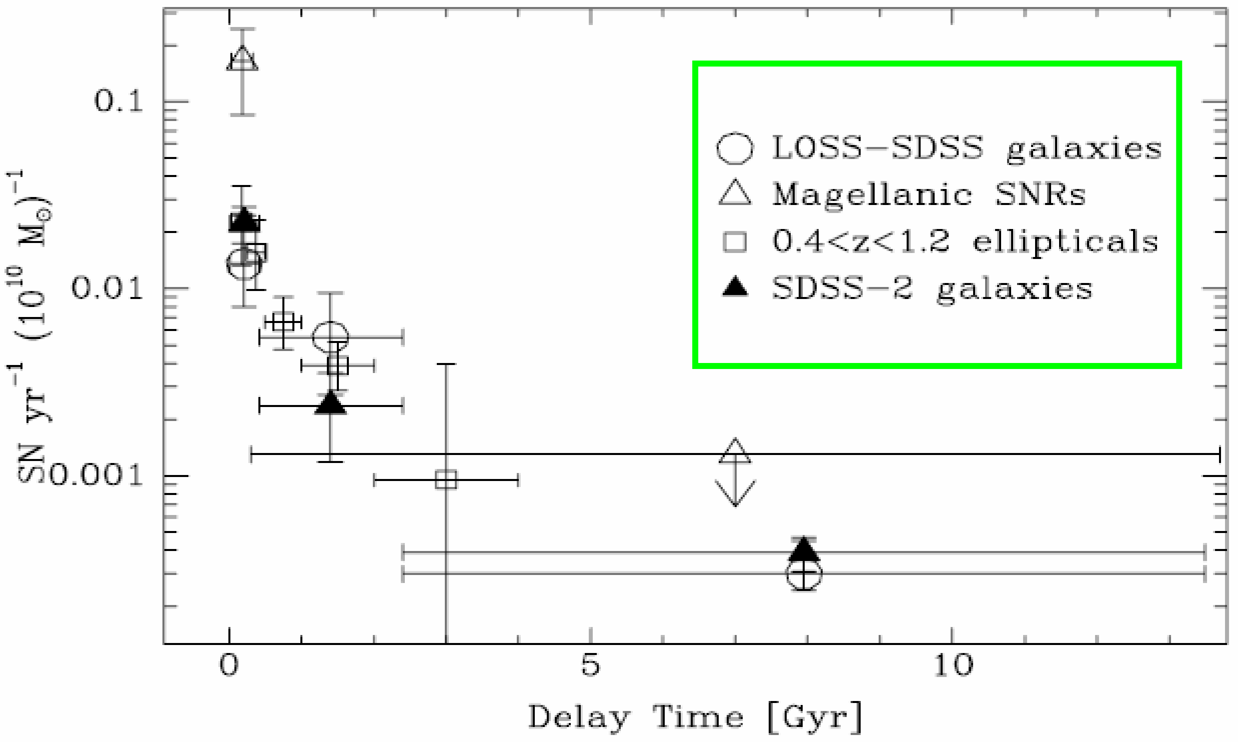
The DTD: a consistent picture emerging.



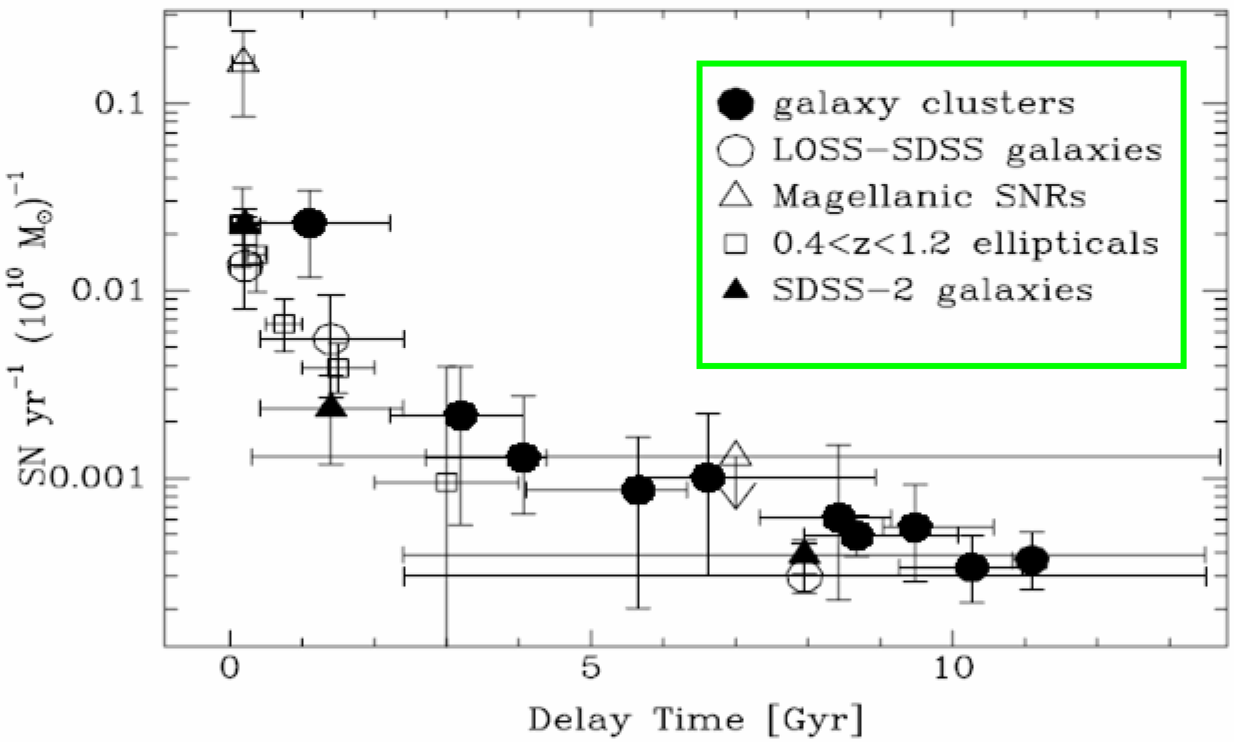
The DTD: a consistent picture emerging.



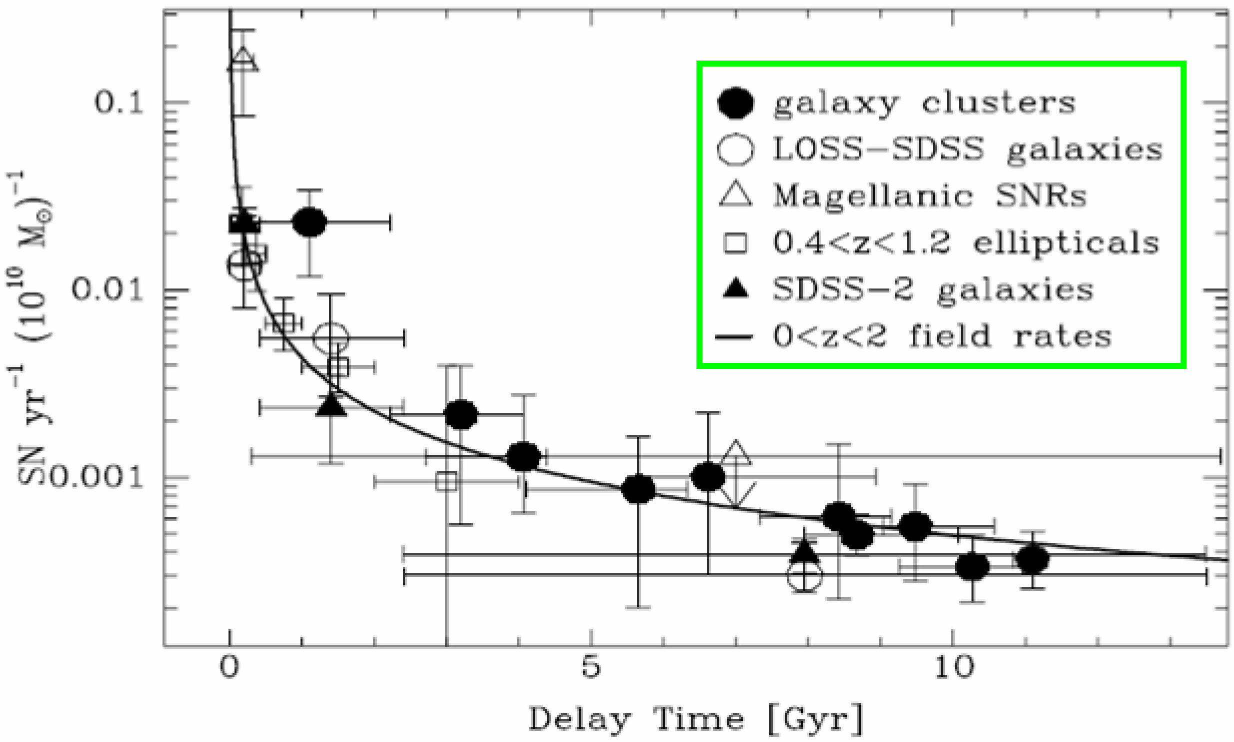
The DTD: a consistent picture emerging.



The DTD: a consistent picture emerging.



The DTD: a consistent picture emerging.

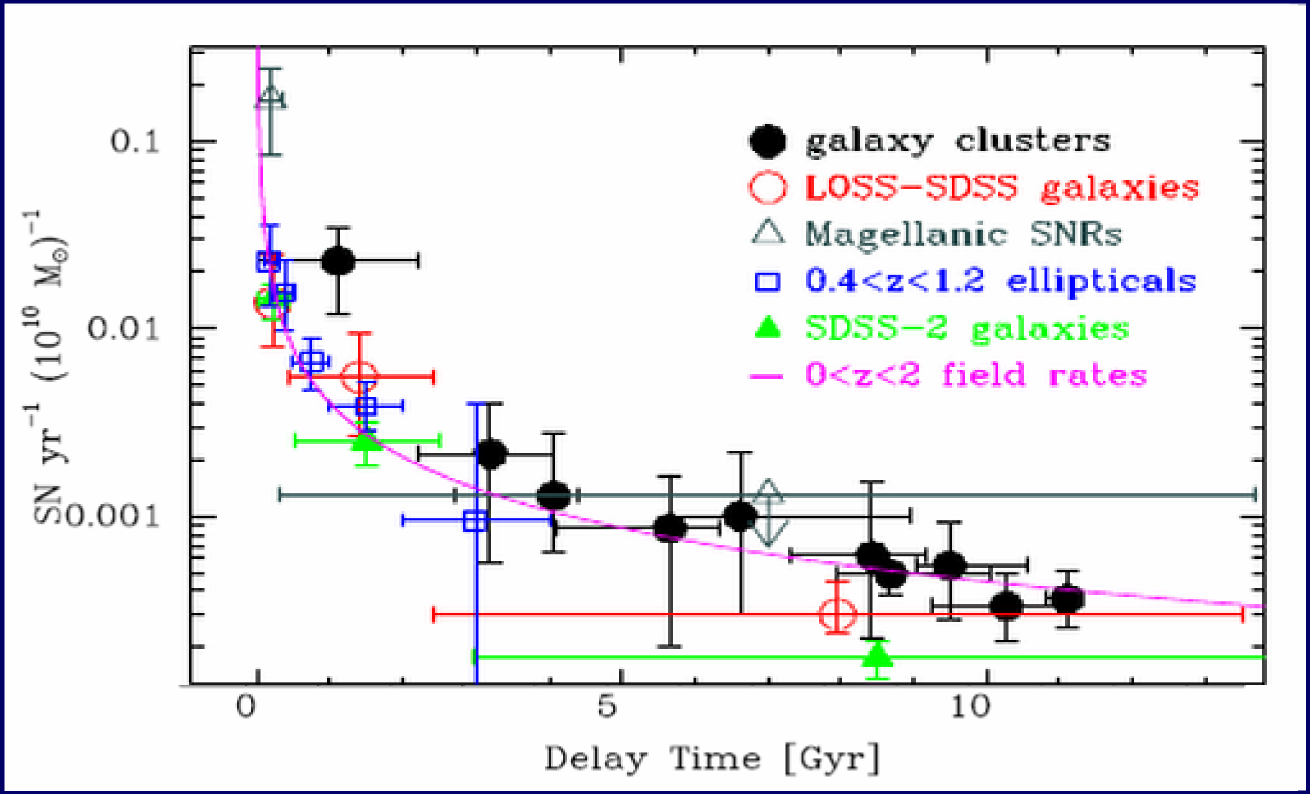


The DTD: a consistent picture emerging.

Emerging Picture:

* Wide distribution of delay times, looks like ~ t^{-1} (DD?)

* >1/2 of SNe-Ia prompt (< 1 Gyr)



Emerging Picture:

* Wide distribution of delay times, looks like ~ t^{-1} (DD?)

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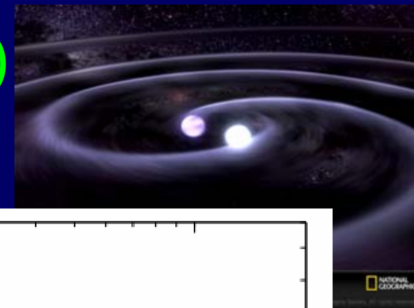
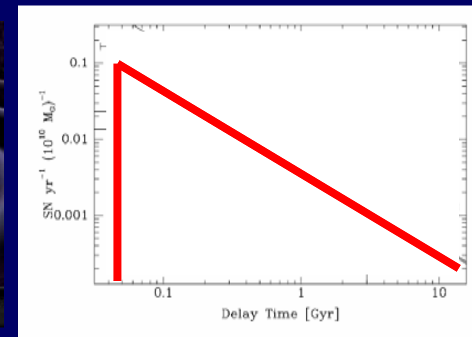
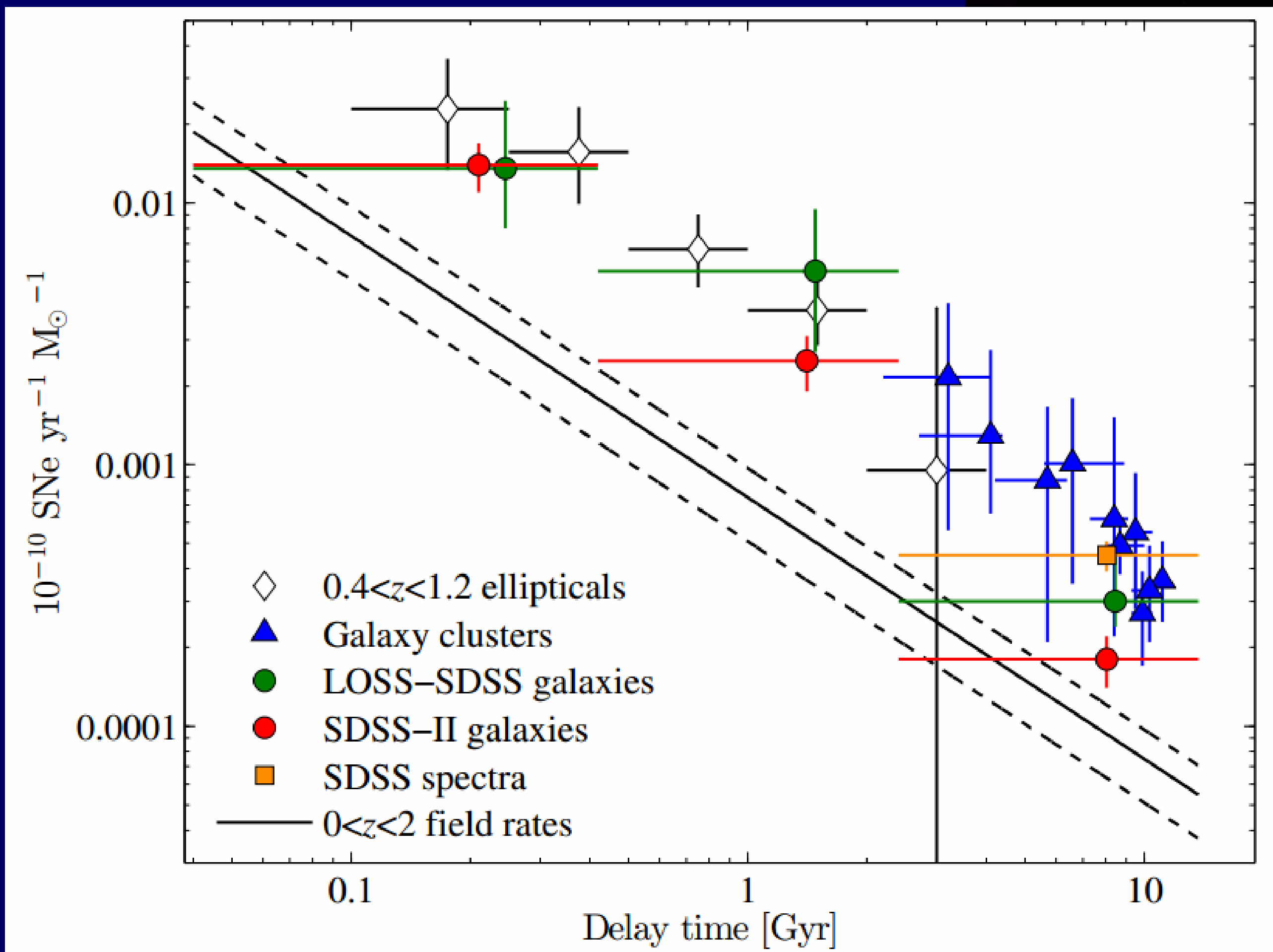
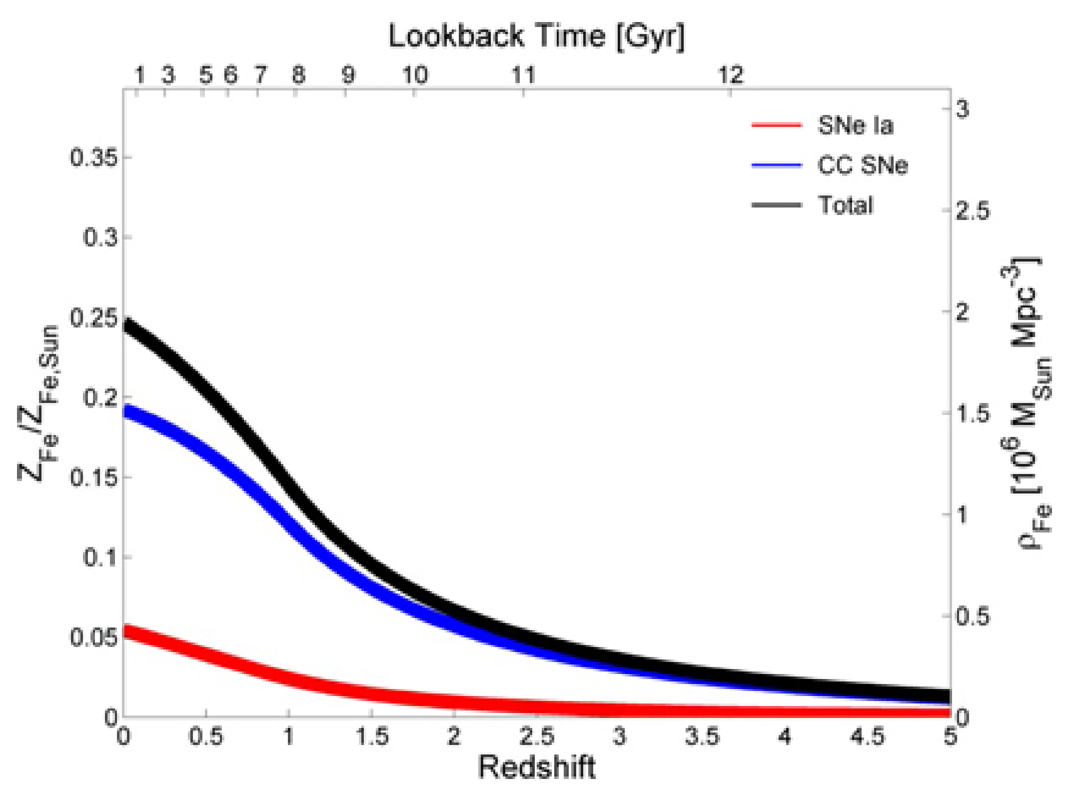






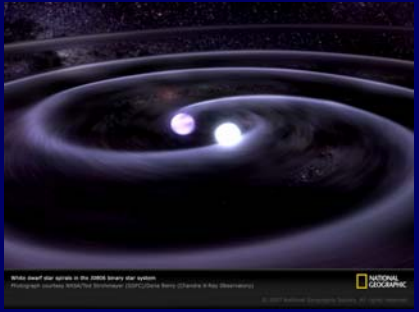
Graur & Maoz 2012

- SN rates now give direct measure of metal accumulation over most of cosmic history

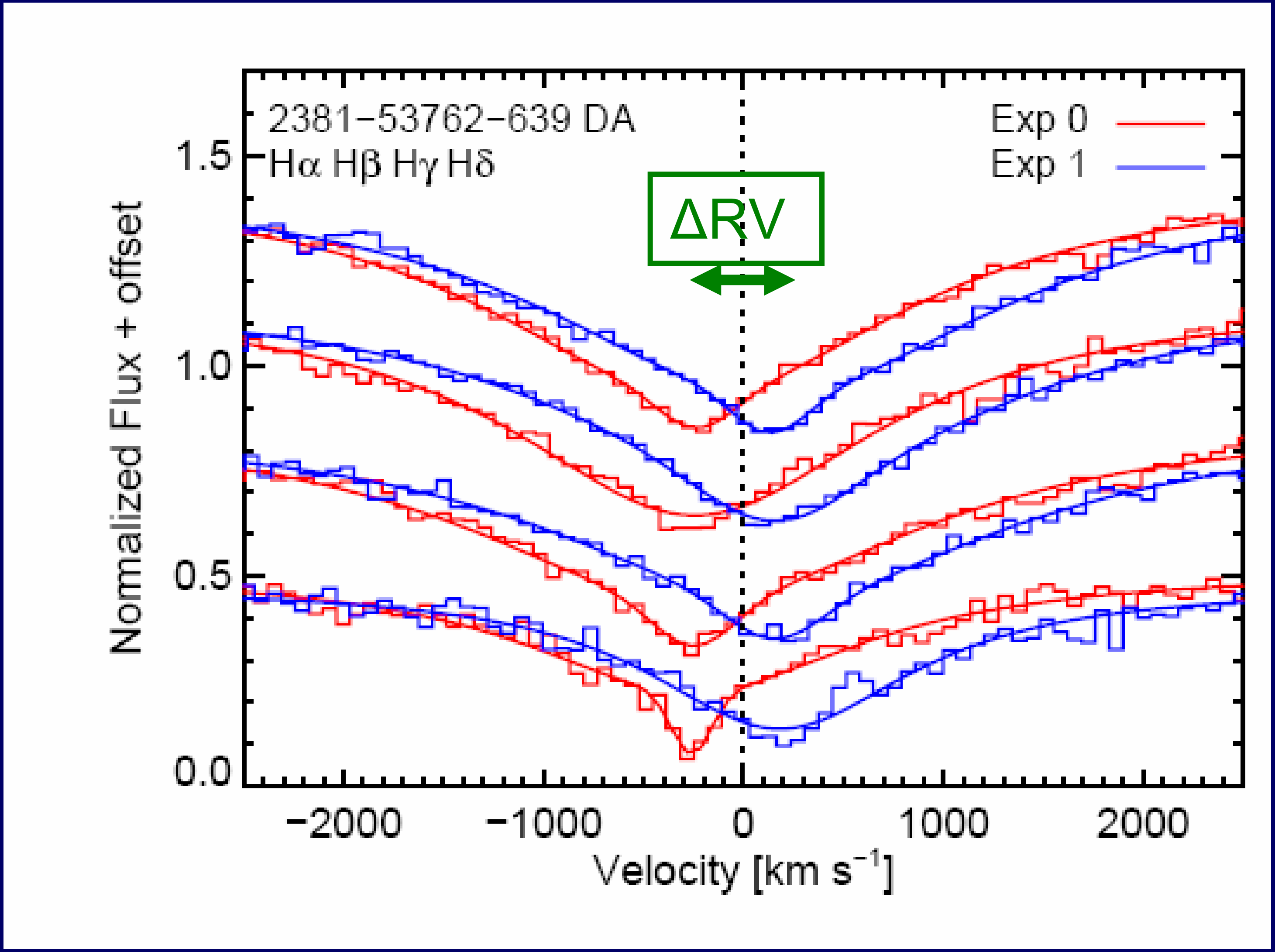


Complementary approach to measuring SN Ia DTD:

Measure, in Milky Way, merger rate of the putative progenitors -- binary white dwarfs



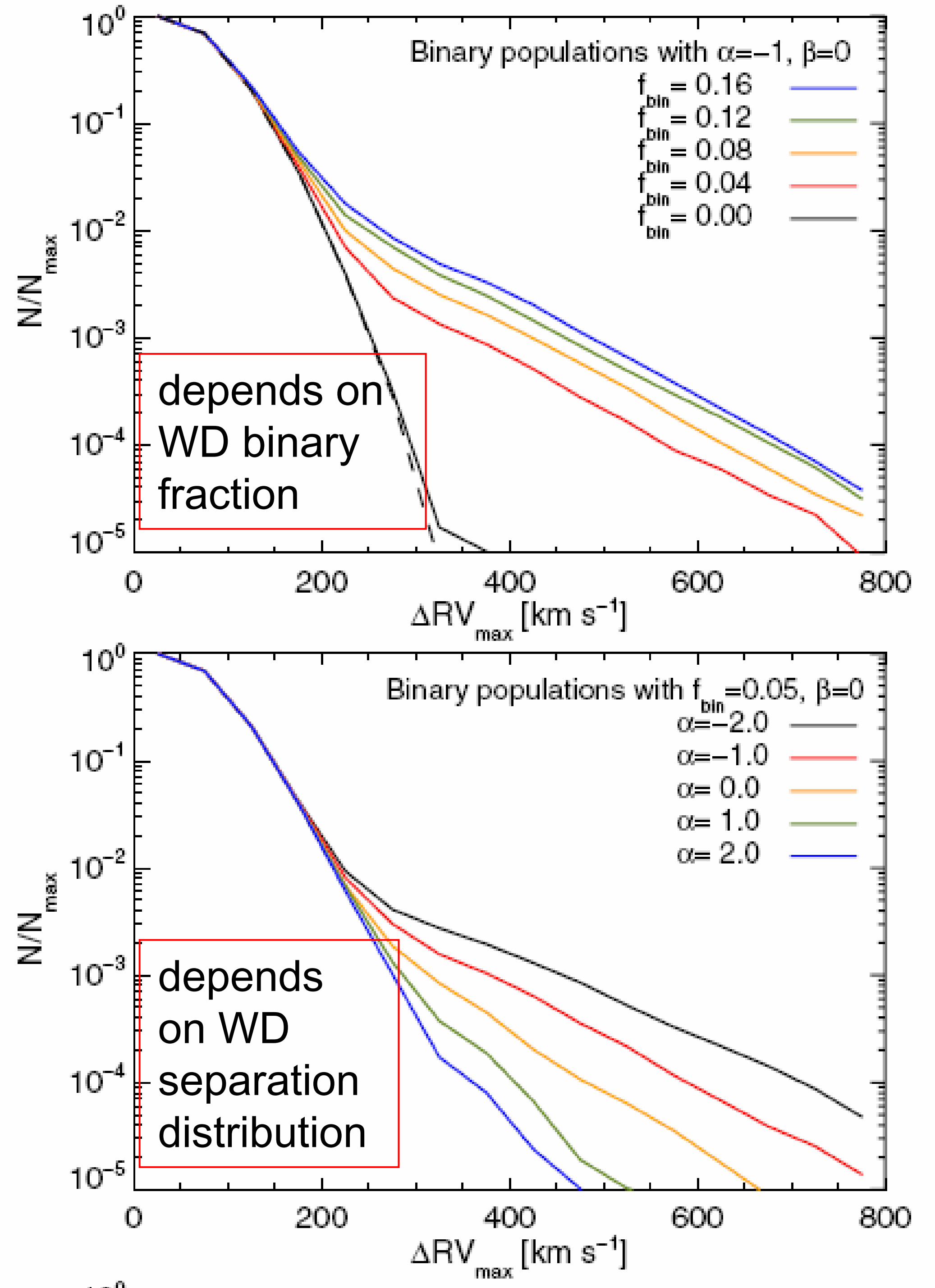
SWARMS survey (PI Badenes): all SDSS spectra, incl. ~10,000 WDs, have spectra from multiple (2-3) epochs



Maoz Badenes Bickerton 12

Badenes & Maoz 12

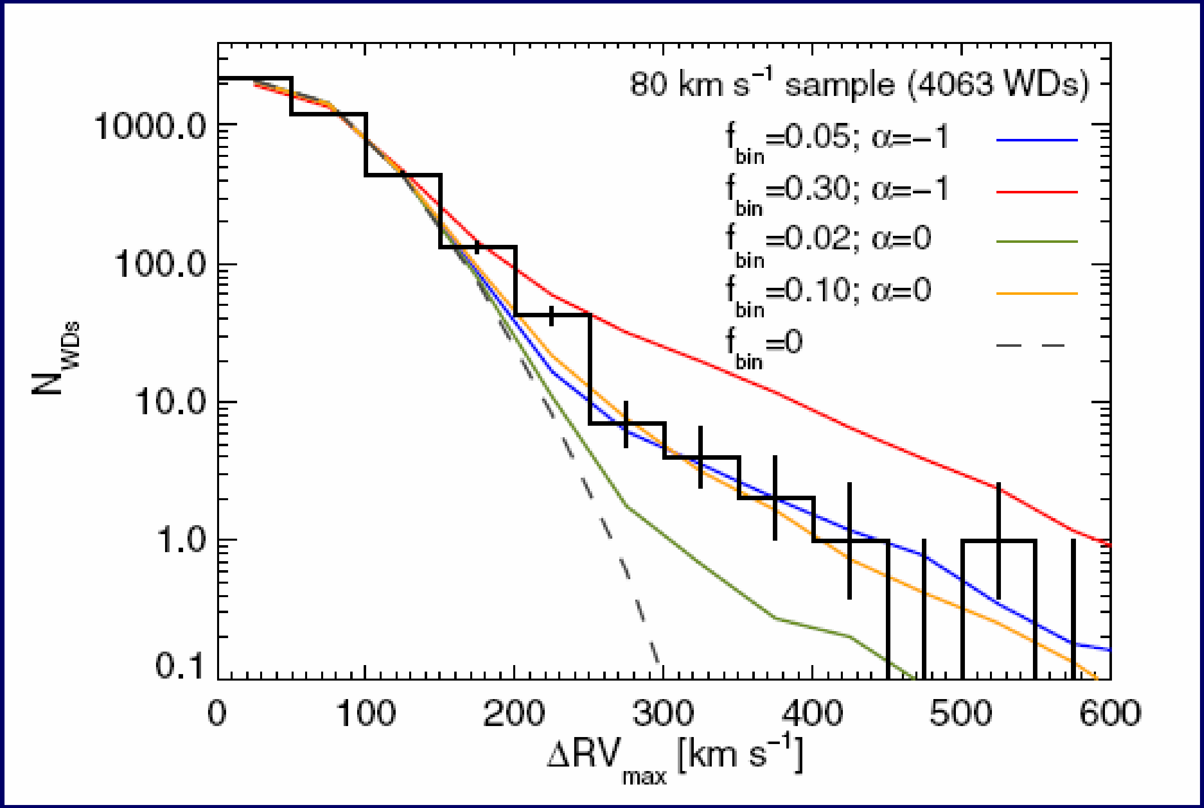
Distribution of maximum velocity differences between epochs has tail that reveals close WD binaries

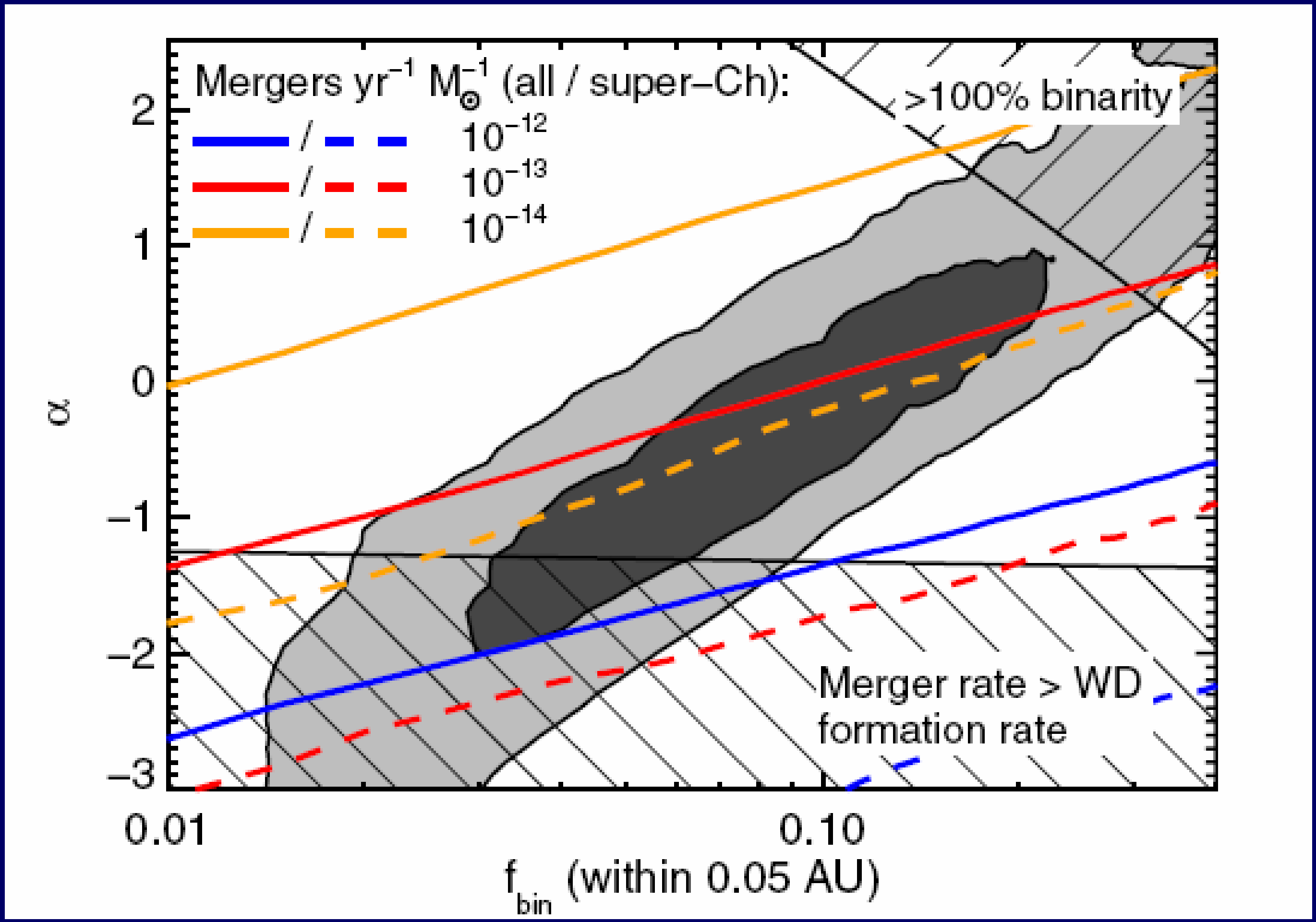


Maoz Badenes Bickerton 12

Badenes & Maoz 12

Observed distribution discriminates among models:





Best-fit model for binary parameters distribution implies total WD merger rate ~ 1×10^{-13} yr^{-1} M$_\odot$ $^{-1}$

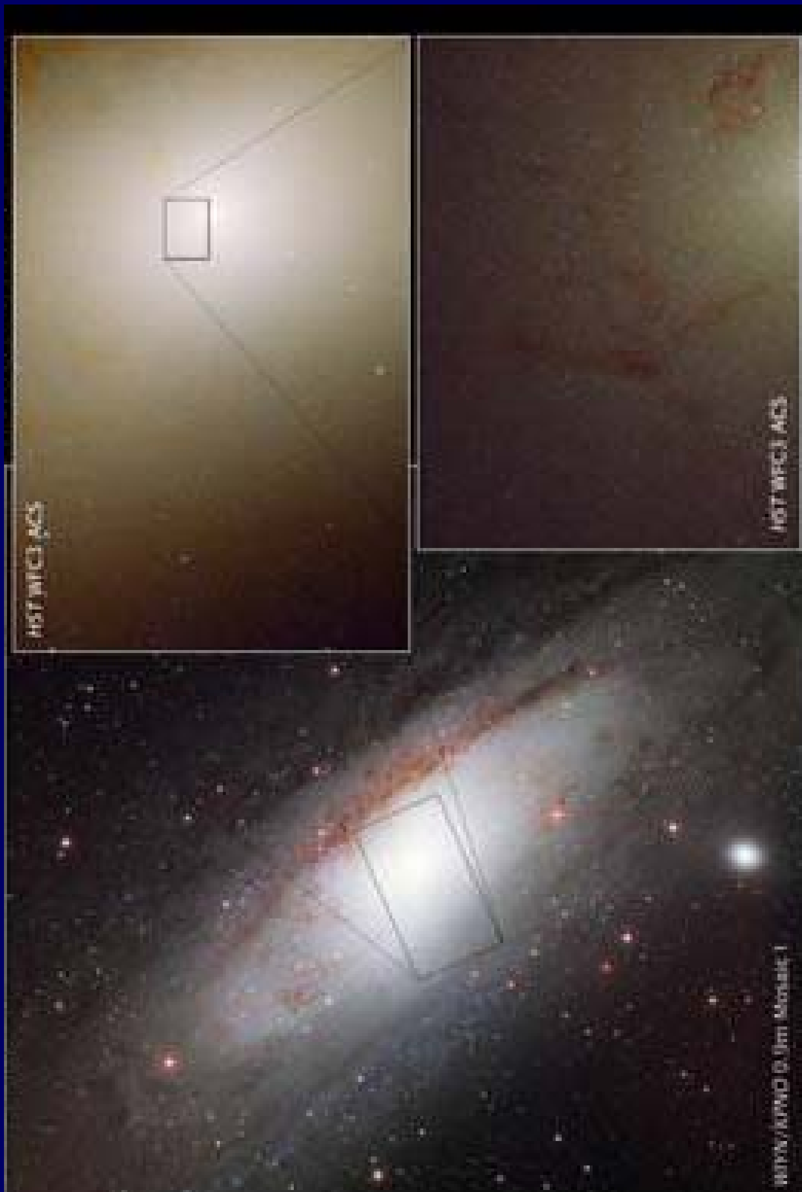
= SN Ia rate per stellar mass in Sbc galaxies (MW)!

But: M_chandra merger rate 10x smaller

The future....

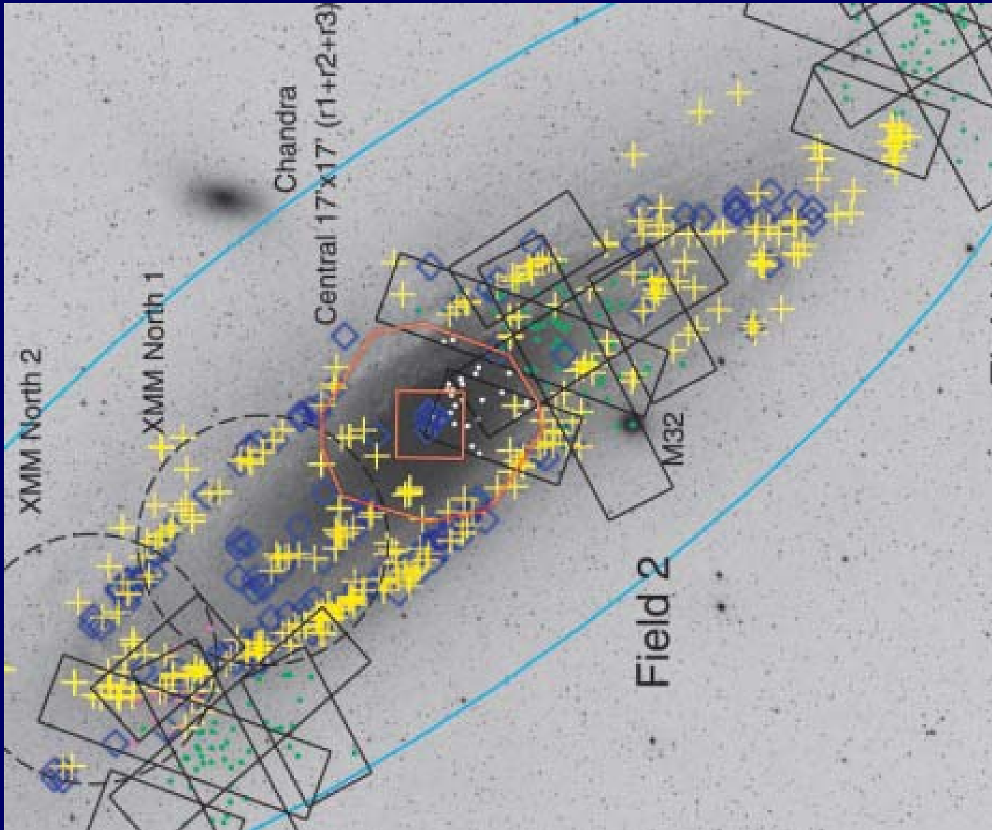
SN rates out to z=2 and beyond with HST
CLASH/CANDELS

Deep SN remnant surveys in additional nearby galaxies with HST-resolved stellar populations (M31, M33).



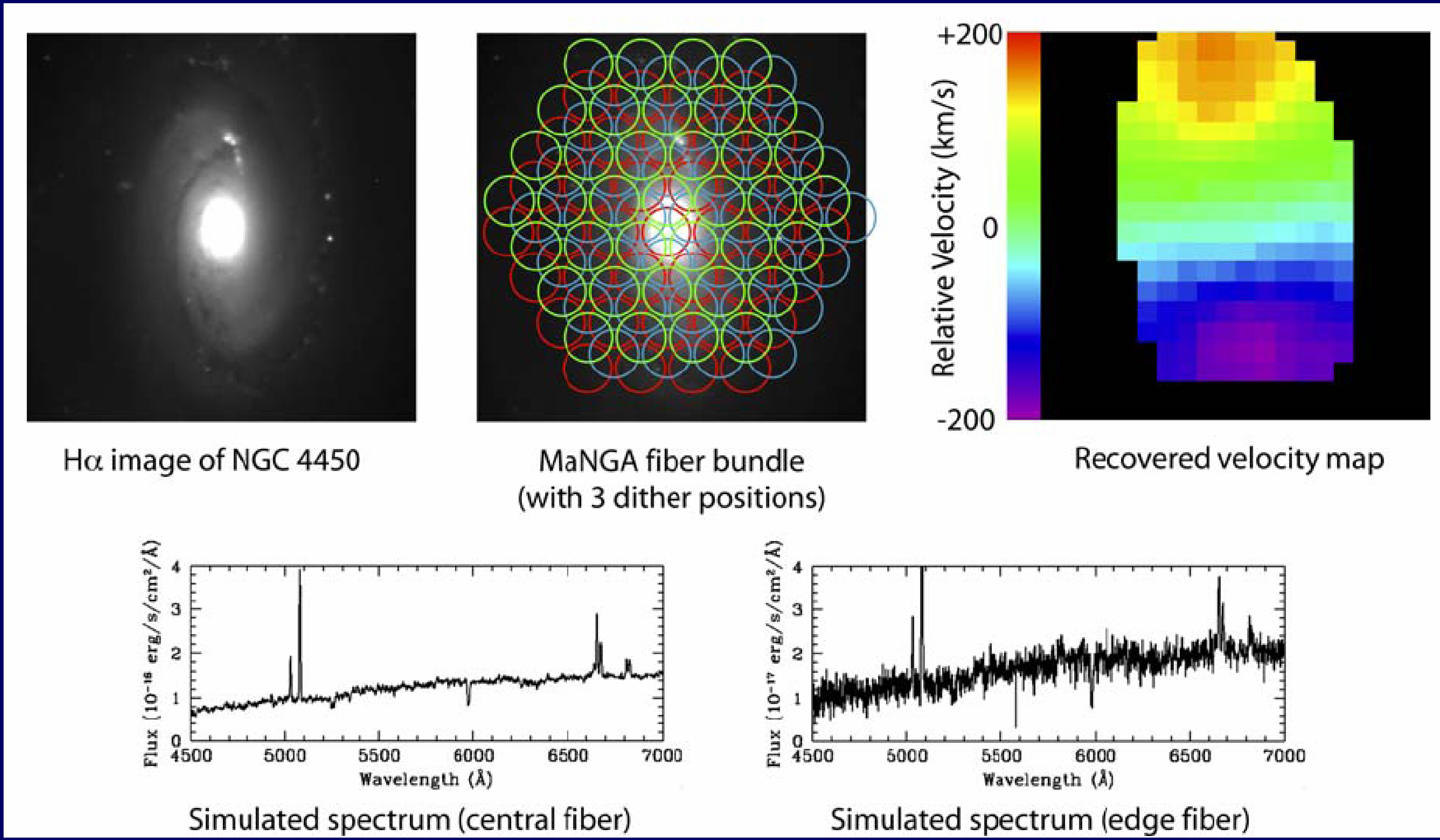
HST-PHAT

Kong+03



Spatially resolved SFHs for galaxies monitored by existing SN surveys

SDSS4-MaNGA (PI K Bundy): IFU spectra for 10,000 nearby galaxies, large overlap with LOSS SN survey



The bivariate distribution of SN delay and explosion energy:

physical link between progenitor and explosion energy

Ruiter+12

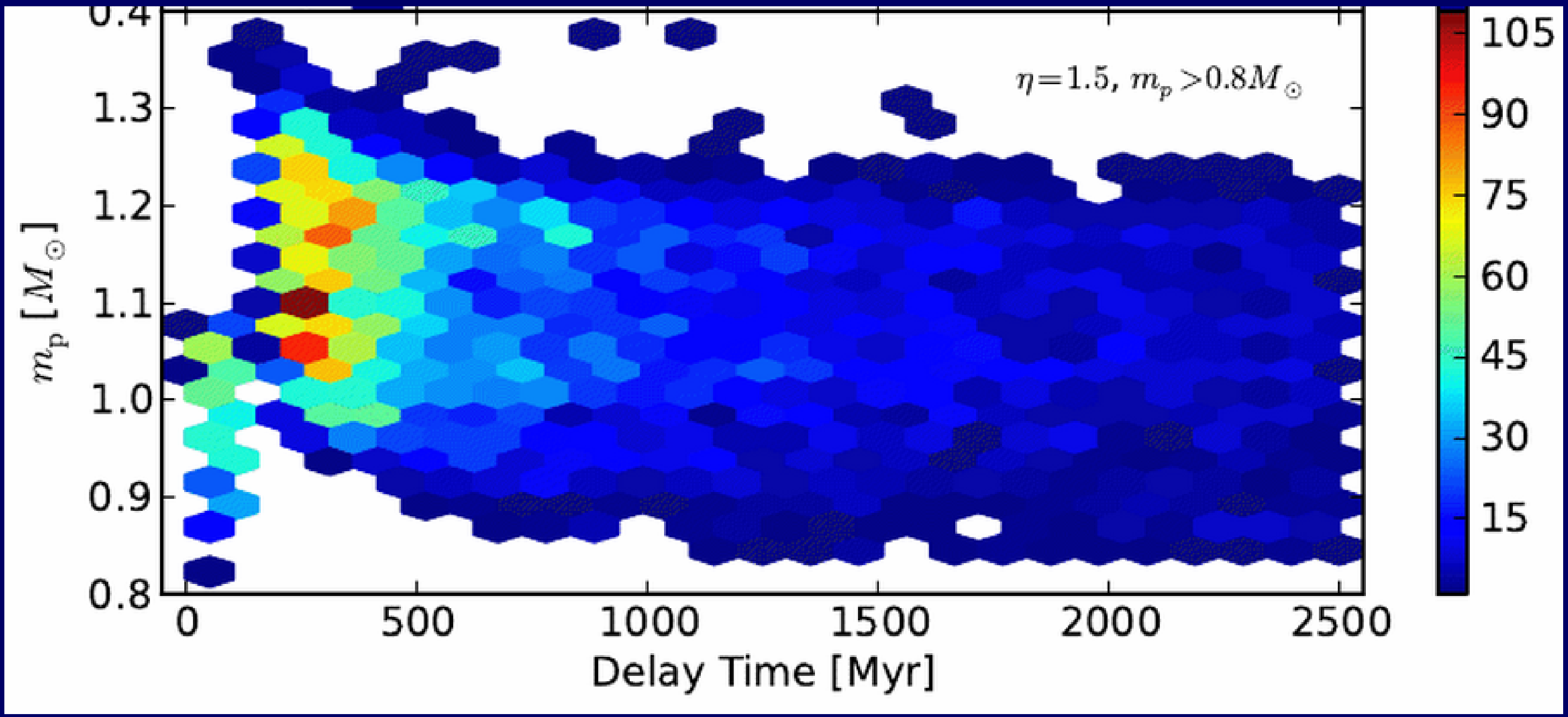
Ni^{56} mass

or

SN luminosity

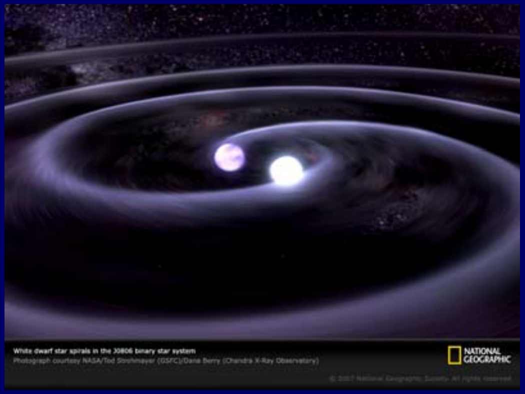
or

stretch



Refine measurement of WD merger rate with larger RV samples / more WDs:

SPY, BOSS, e-BOSS, super-BOSS



Summary

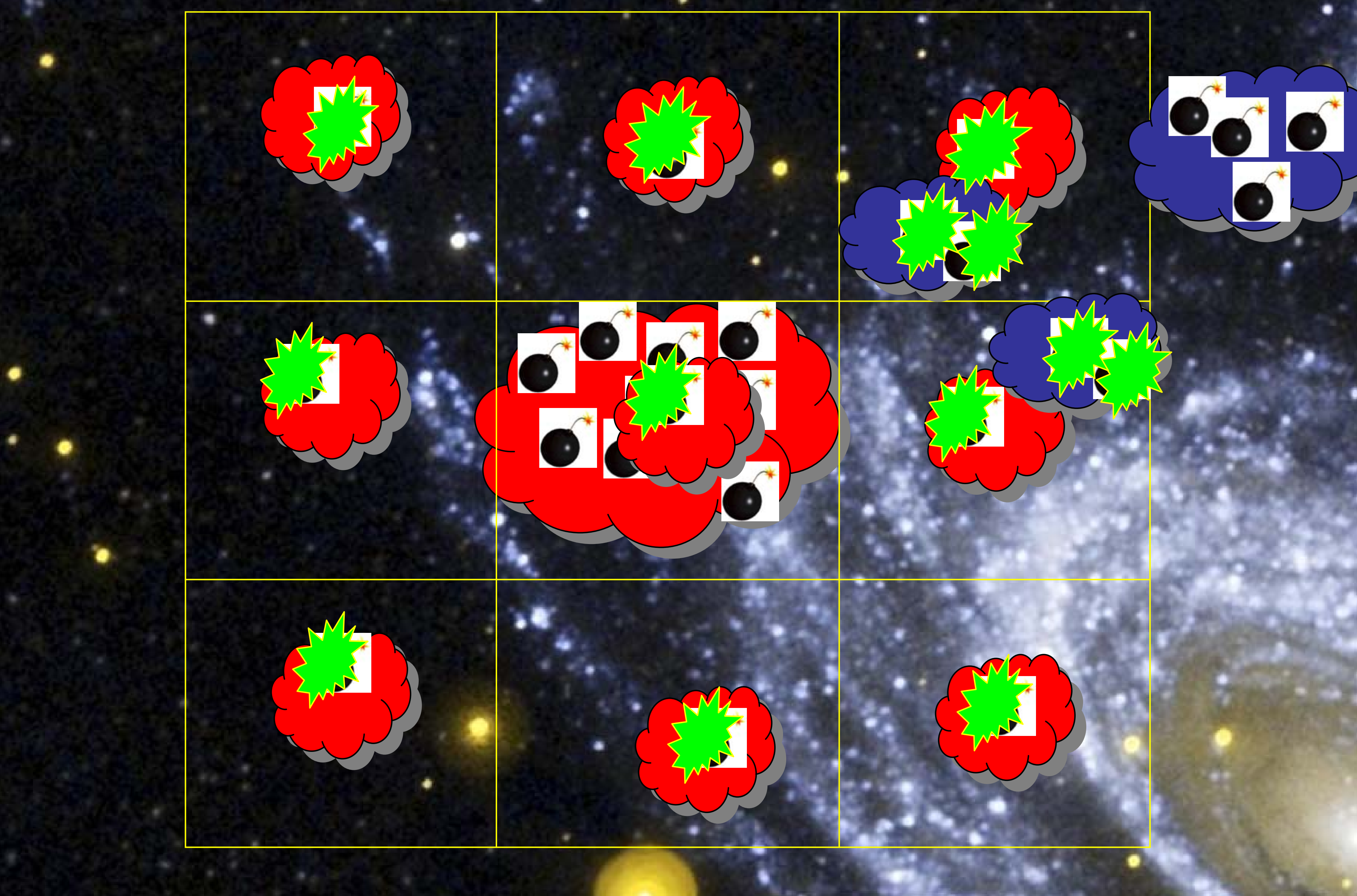
1. Assortment of samples and techniques indicate DTD is $\sim t^{-1}$ power law. =DD progenitors? Can SD, CD, give such DTDs?

2. DTD normalization may vary: higher SN Ia production in cluster/massive galaxy environments? Related to IMF efects?

3. Local Galactic WD merger rate matches specific SN Ia rate in MW-like galaxies. But, $>M_{Chandra}$ WD merger rate may be lower. Do sub-chandra mergers make SNe Ia? Maybe observed DD pairs are not the progenitors?

4. Many remaining ways to refine observed DTD and WD merger rate: high-z rates; SNR surveys, localized galaxy SFHs, bivariate delay/energy distr.; more WD RV surveys

Every region still has correct ratio of SNe/(stellar mass of given age).



Problems with both scenarios

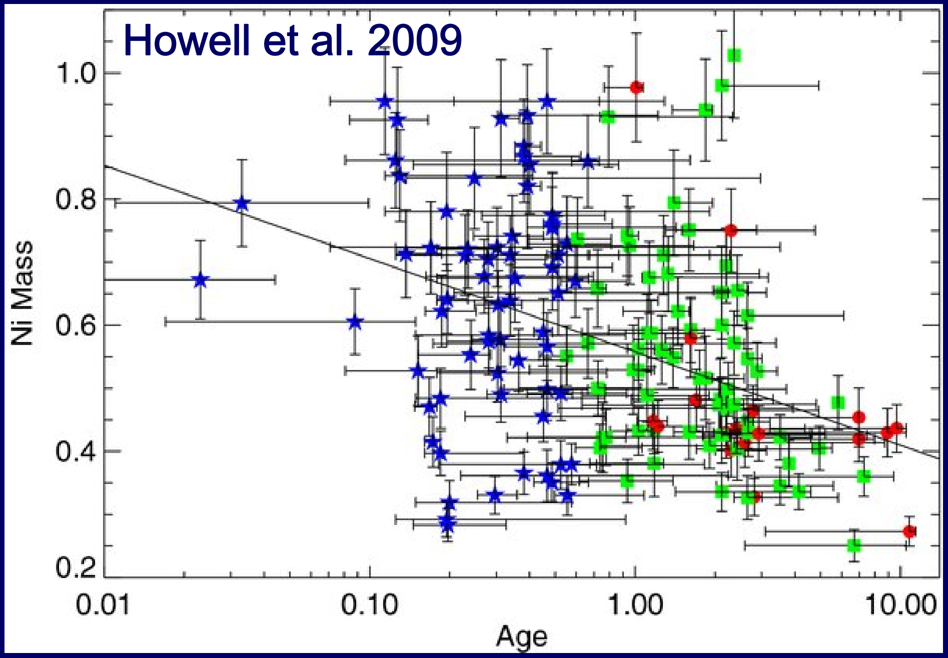
Energetics and spectra don't come out right, unless finely (and artificially) tuned "Deflagration Delayed Detonation" (Khochlov 1991)

Why is there a range of luminosities if always M_chandra? (Phillips 1993)

Why is there dependence of luminosity (=Ni mass) on age of host?

Predicted rates are too low (Maoz 2008; 2010; Ruiter+2008; Mennekens+2010)

Sim+2010; Van Kerkwijk+2010 – sub M_chandra mergers could solve problems

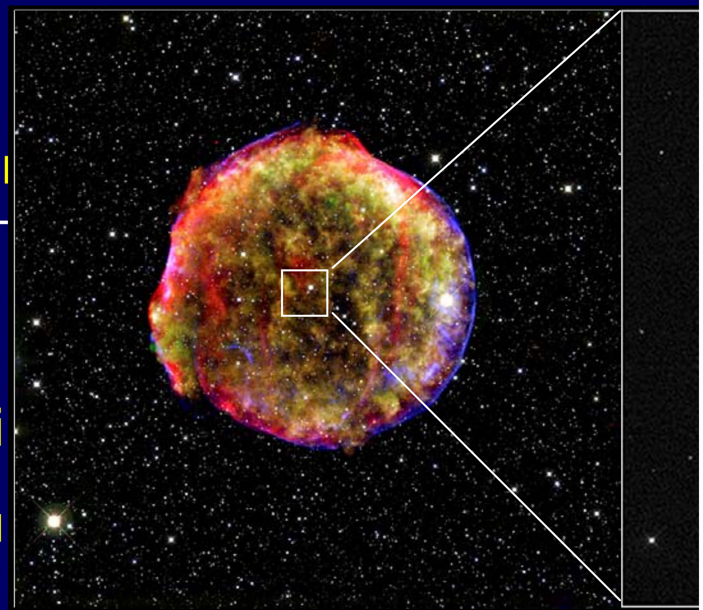


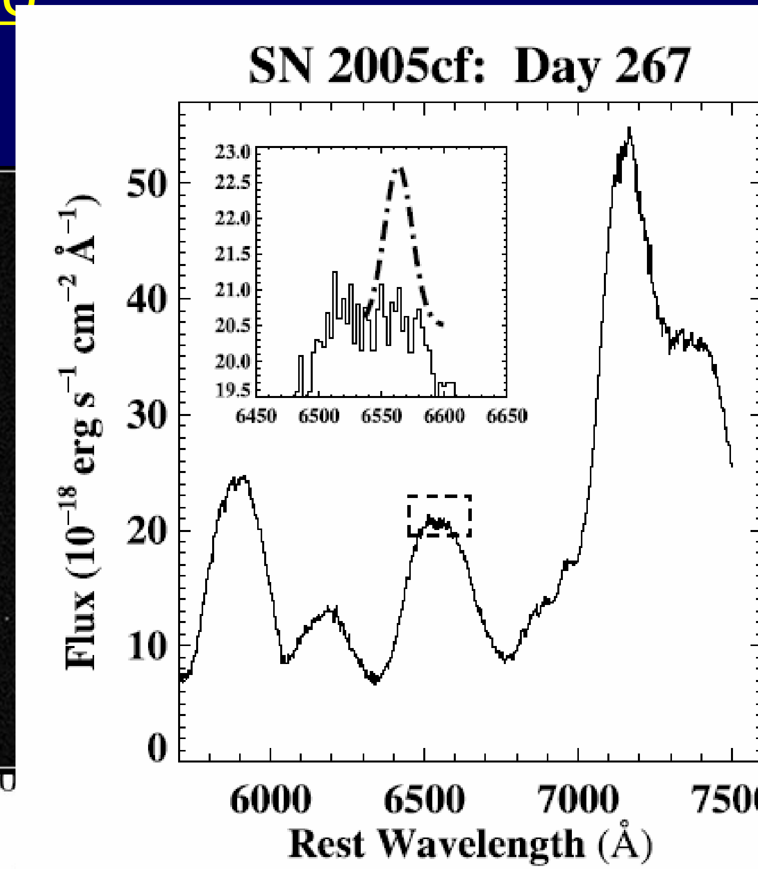
Problems with each progenitor scenario

SD:

Theory:

(Too)-fine tuning r
(Hachisu+99;Cassisi+





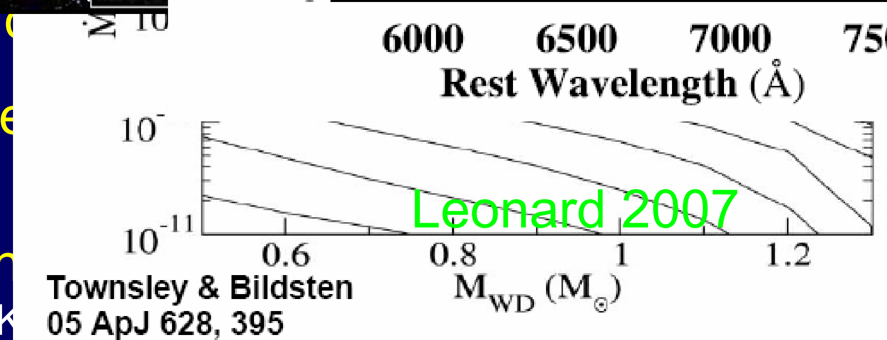
Observation:

Wind signatures i

No H, He in nebu

SNe-Ia seen in low-metallicity galaxies, c

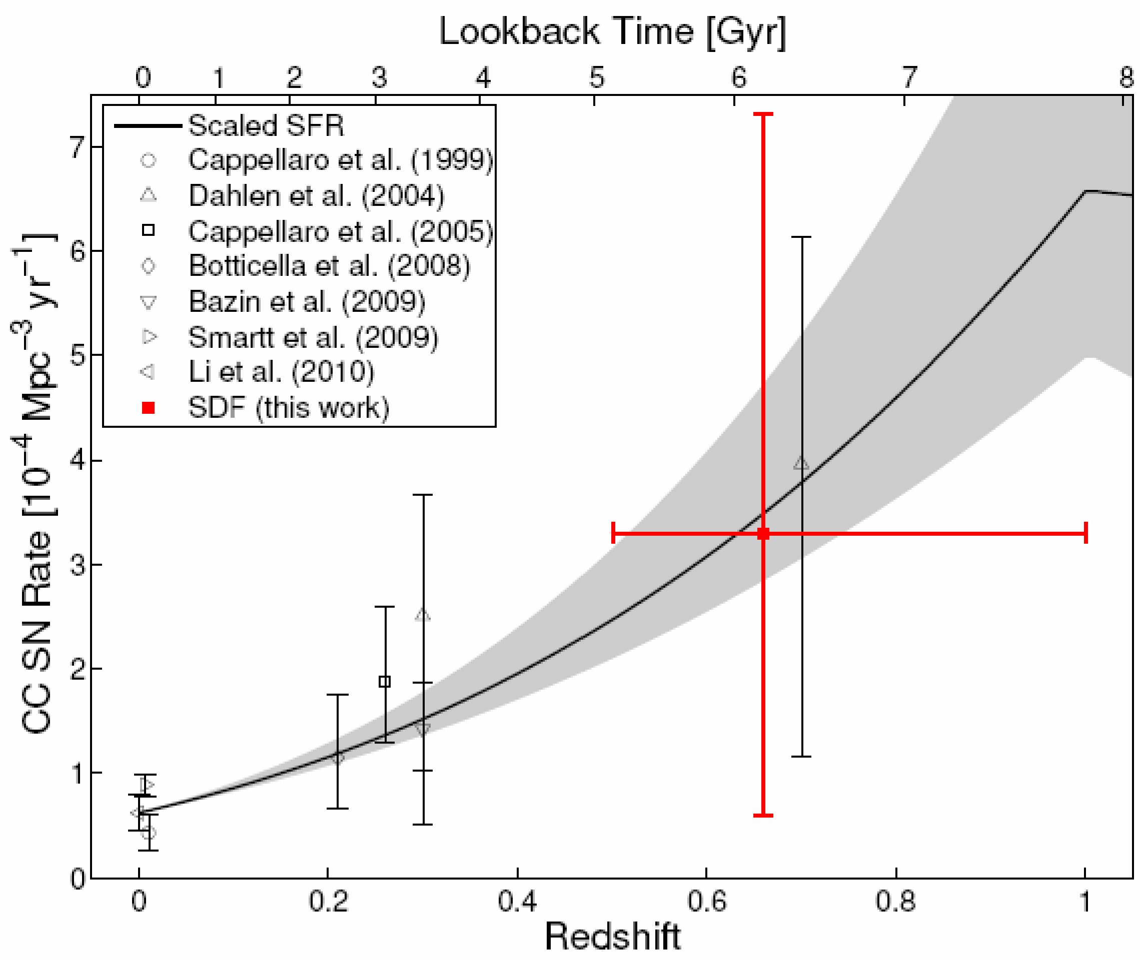
NaD absorption (=CSM?) found in some
Yourdon 2008; Simon+09)



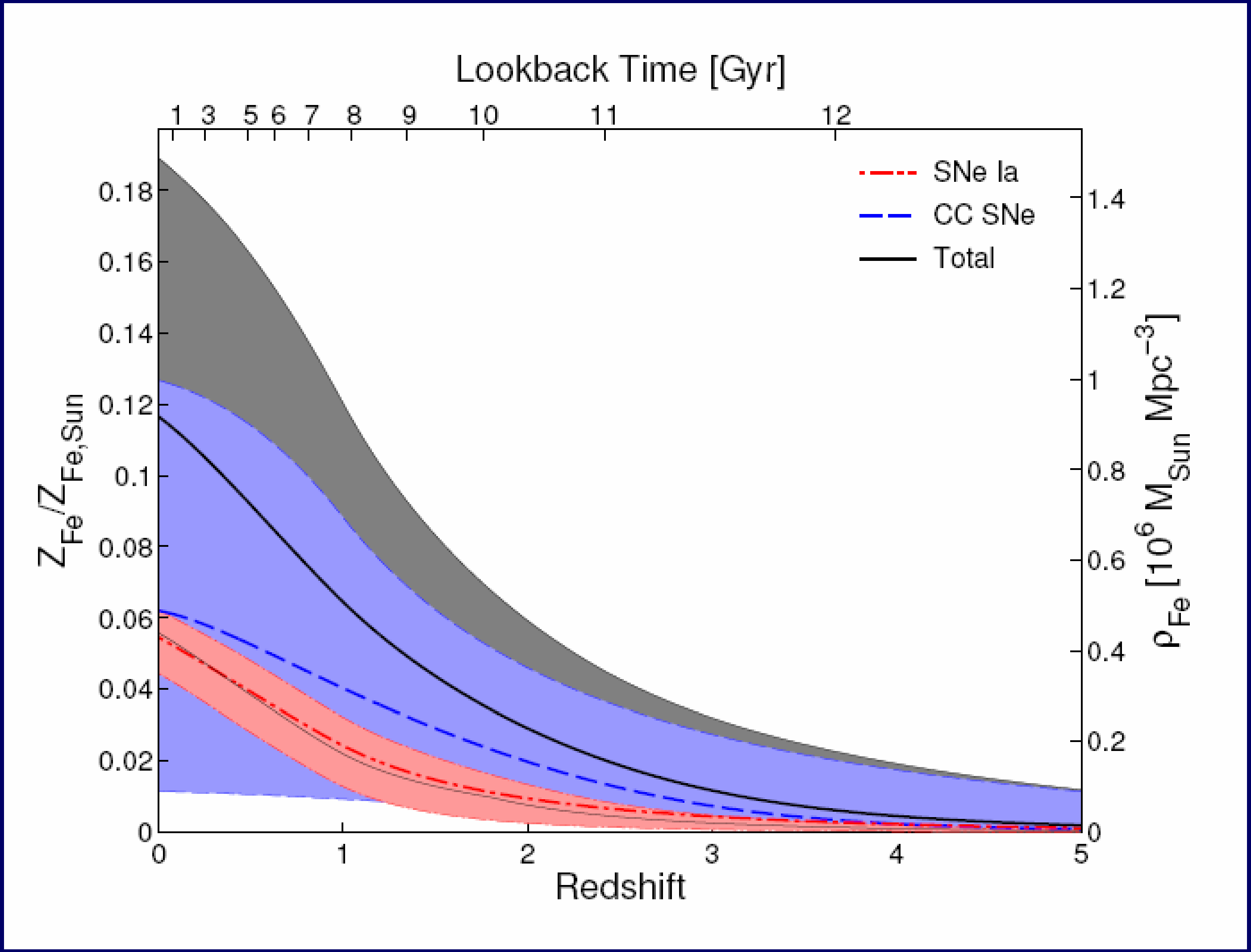
Leonard 2007

No agreed ID of remaining companion in
2005, Ihara+ 2007, Gonzalez-Hernandez+ 2008, K

Where are the nuclear-burning accreting WDs (SSXS)? (di Stefano 2010; Gilfanov & Bogdan 2010; but see Hachisu+10, diStefano+2011)



Lookback Time [Gyr]
0
1
2
3
4
5
6
7
8
Scaled SFR
Cappellaro et al. (1999)
Dahlen et al. (2004)
Cappellaro et al. (2005)
Botticella et al. (2008)
Bazin et al. (2009)
Smartt et al. (2009)
Li et al. (2010)
SDF (this work)
CC SN Rate [10^-4 Mpc^-3 yr^-1]
0
1
2
3
4
5
6
7
0
0.2
0.4
0.6
0.8
1
Redshift



Lookback Time [Gyr]
1 3 5 6 7 8 9 10 11 12
SNe Ia
CC SNe
Total
$Z_{Fe}/Z_{Fe,Sun}$
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18
ρ_{Fe} [10^6 M_{Sun} Mpc^{-3}]
0 0.2 0.4 0.6 0.8 1 1.2 1.4
0 1 2 3 4 5
Redshift