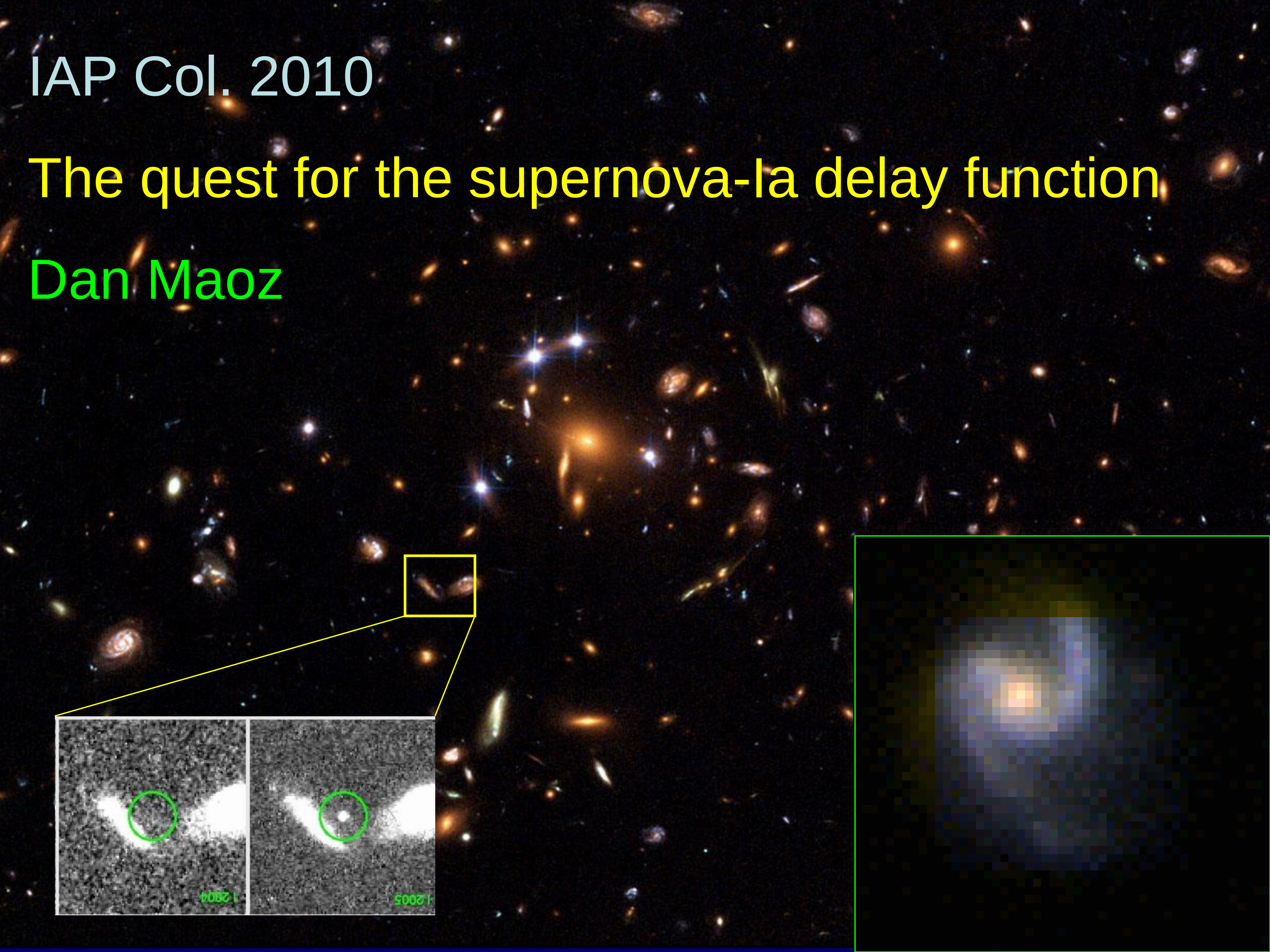
IAP Col. 2010

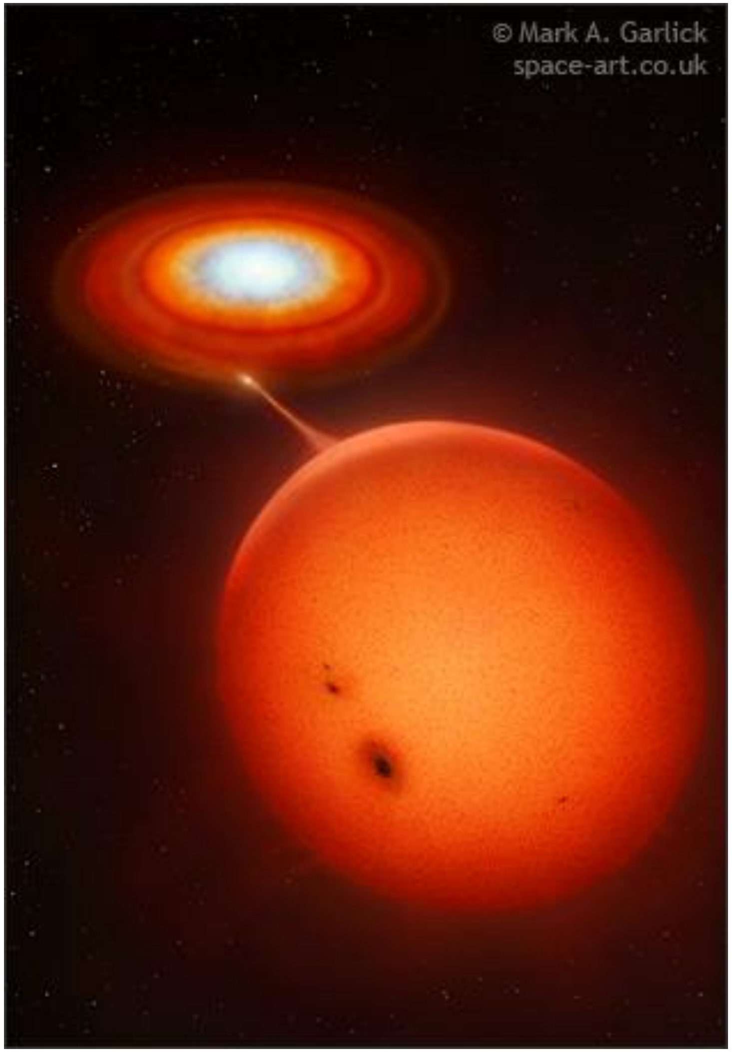
The quest for the supernova-Ia delay function

Dan Maoz

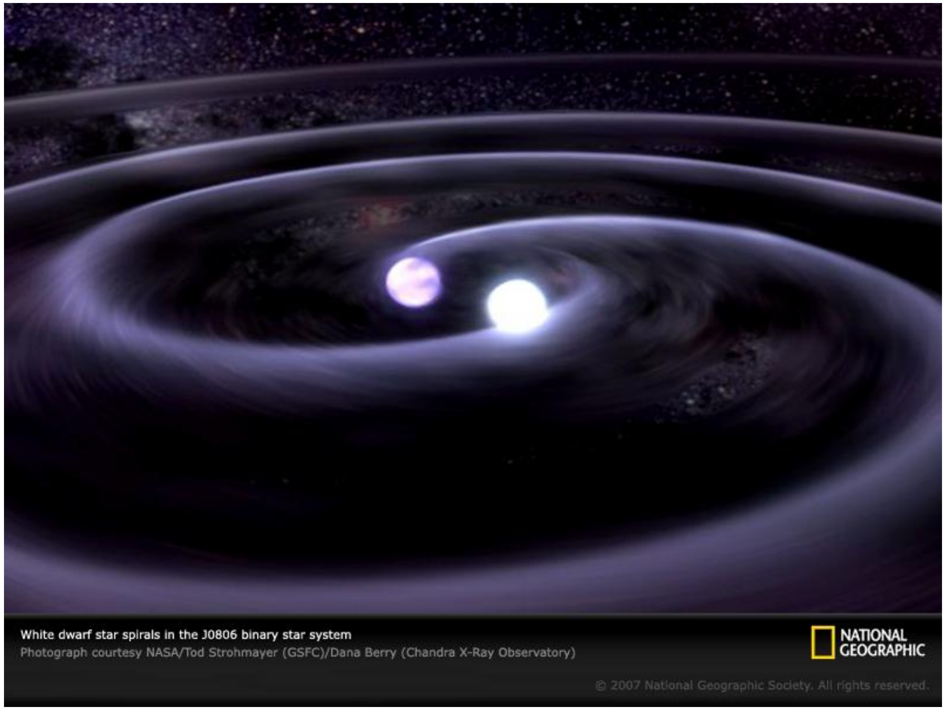


Progenitors?

"single degenerate" ("SD") (Whelan & Iben 1974)



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

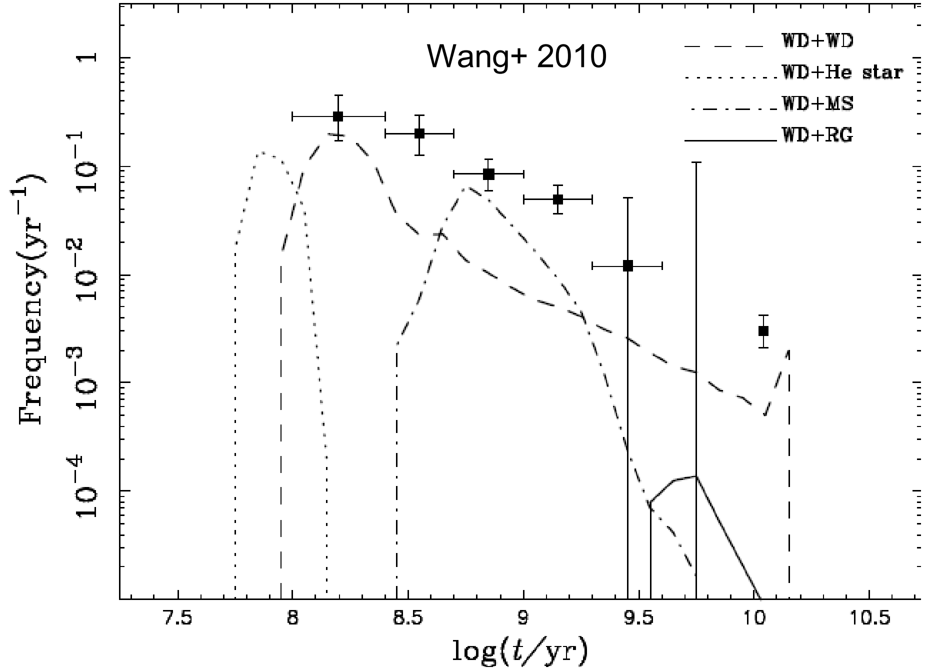


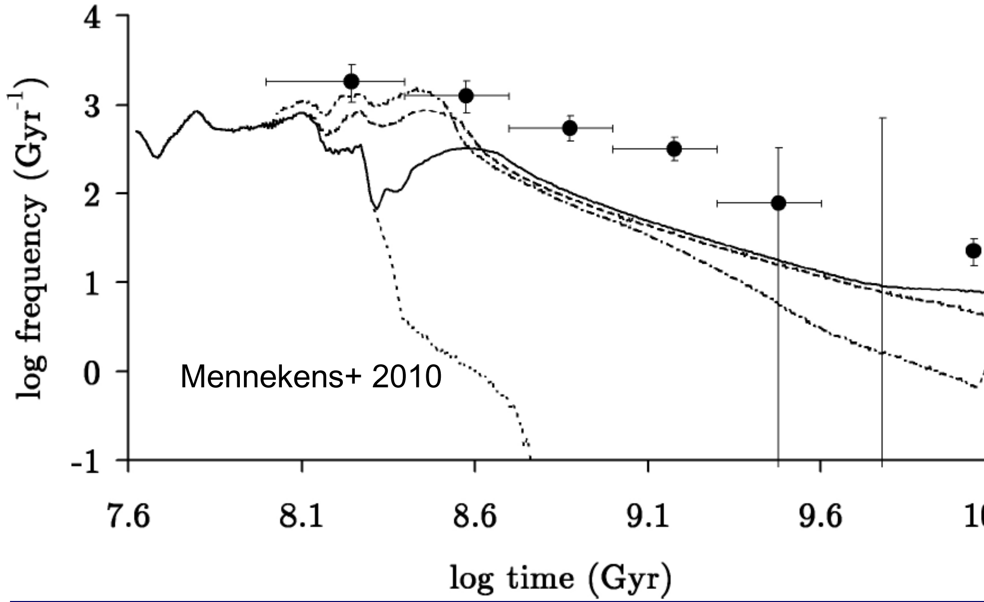
Clues to progenitors can be obtained by measuring SN Rates

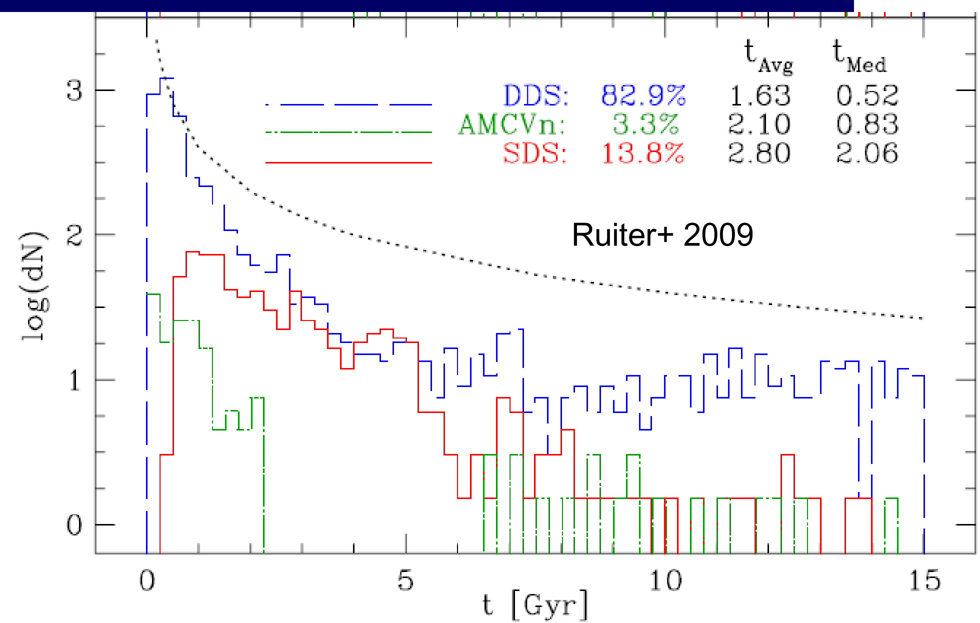
SN Ia “delay time distribution”:

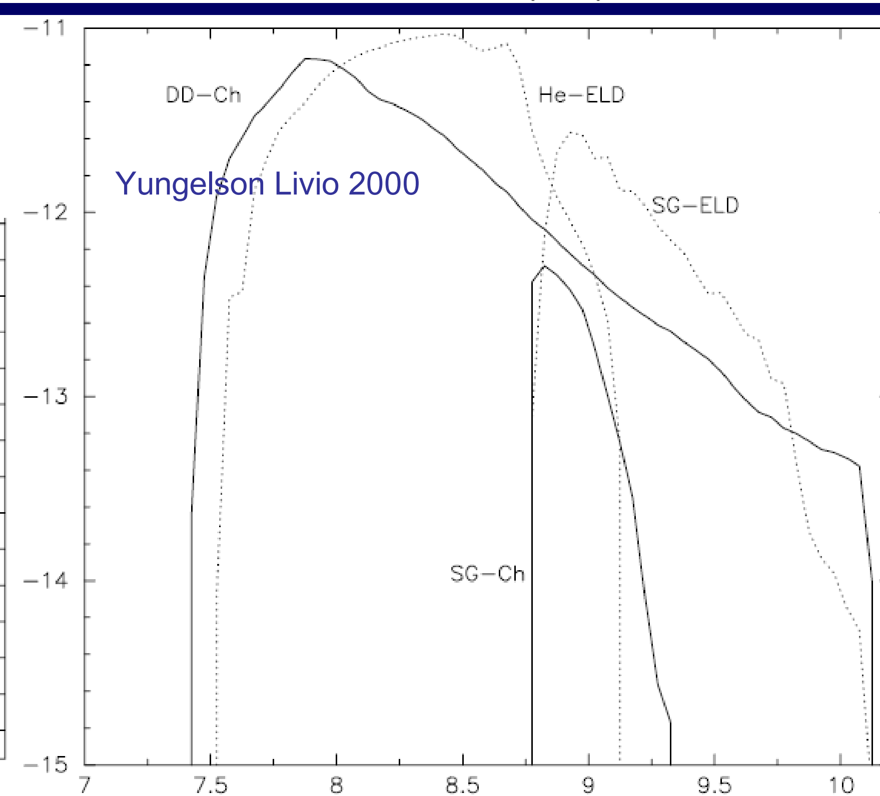
=

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


Wang+ 2010
WD+WD
WD+He star
WD+MS
WD+RG
Frequency(yr^{-1})
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
7.5
8
8.5
9
9.5
10
10.5
log(t/yr)


Mennekens+ 2010
log frequency (Gyr^{-1})
4
3
2
1
0
-1
7.6
8.1
8.6
9.1
9.6
log time (Gyr)

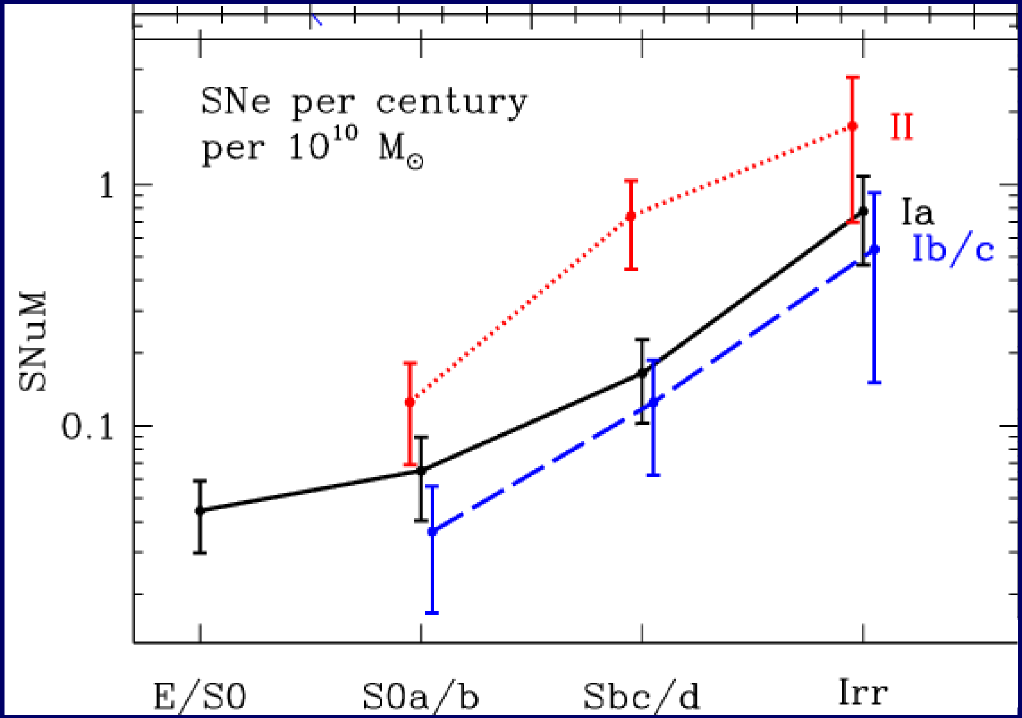

Ruiter+ 2009
t_{Avg}
t_{Med}
DDS: 82.9% 1.63 0.52
AMCVn: 3.3% 2.10 0.83
SDS: 13.8% 2.80 2.06
log(dN)
3
2
1
0
0
5
10
15
t [Gyr]


Yungelson Livio 2000
DD–Ch
He–ELD
SG–ELD
SG–Ch
−11
−12
−13
−14
−15
7
7.5
8
8.5
9
9.5
10

How to recover the delay time distribution

I. SN Rates vs. galaxy “age”

A first crack at the delay function (Mannucci et al. 2005): compare SN rate in blue (“young”) and red (“old”) galaxies.



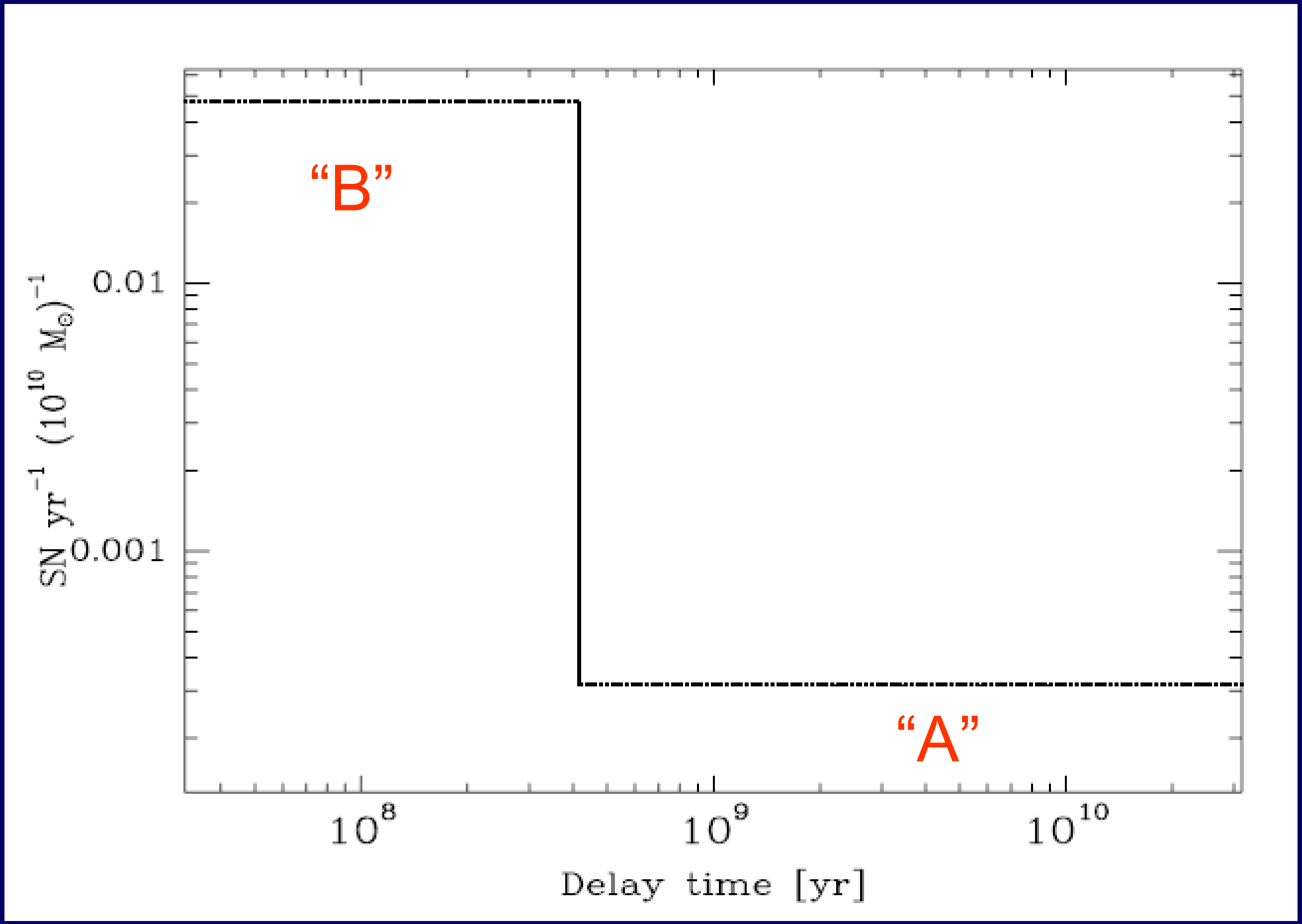
SN-Ia rate is proportional to color! (star-formation rate)

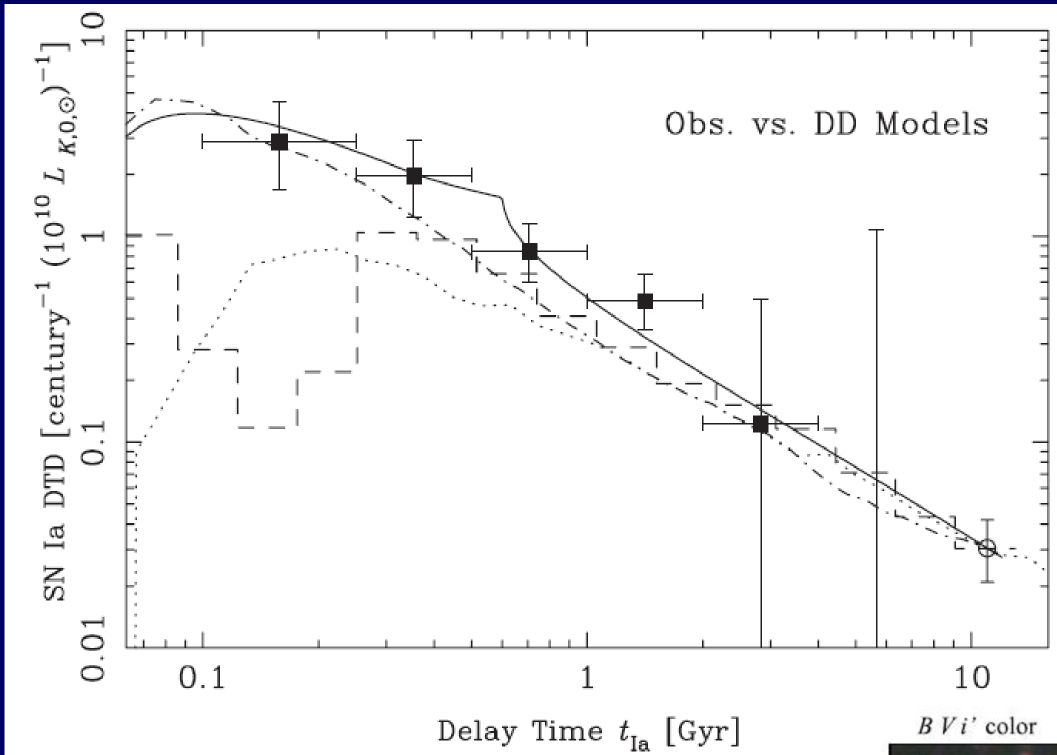
some SNe-Ia : “prompt” (<0.5 Gyr)

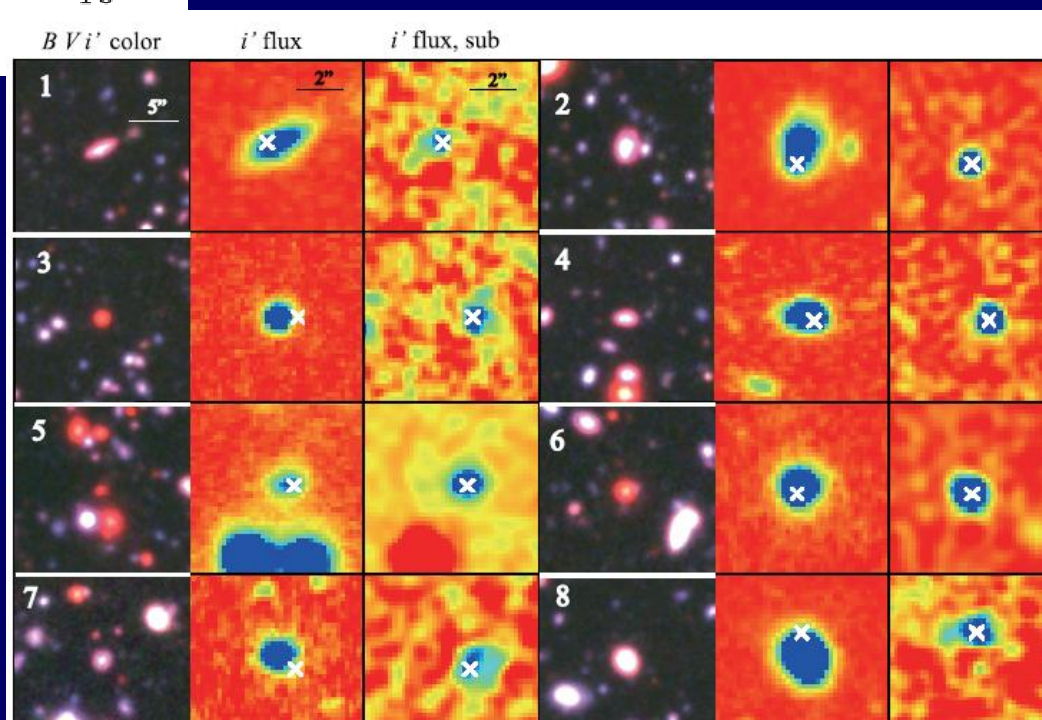
and

some SNe-Ia “delayed” (~5 Gyr)

"A+B" model (Mannucci+05; Scannapieco & Bildsten 05; Sullivan+ 06)







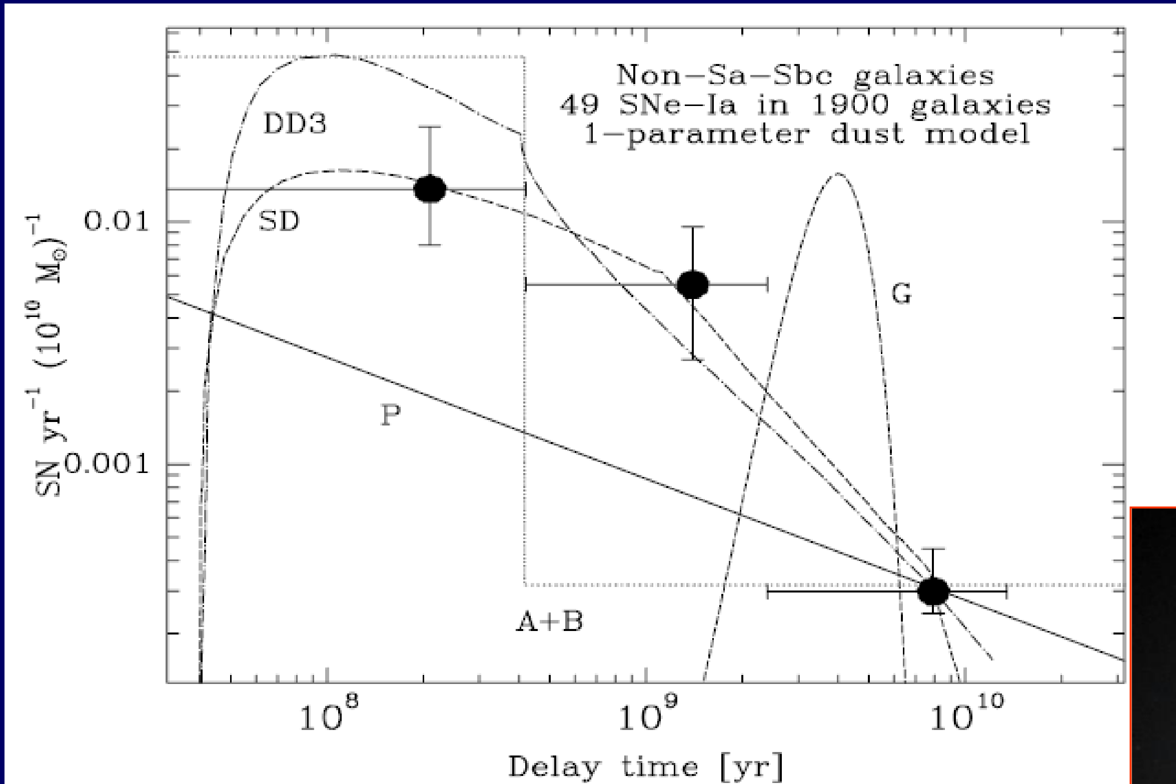
Totani et al. 2008

SN rates in E galaxies at z=0.4-1.2

Similar results by Okumura+ for non-E galaxies.

How to recover the delay time distribution

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



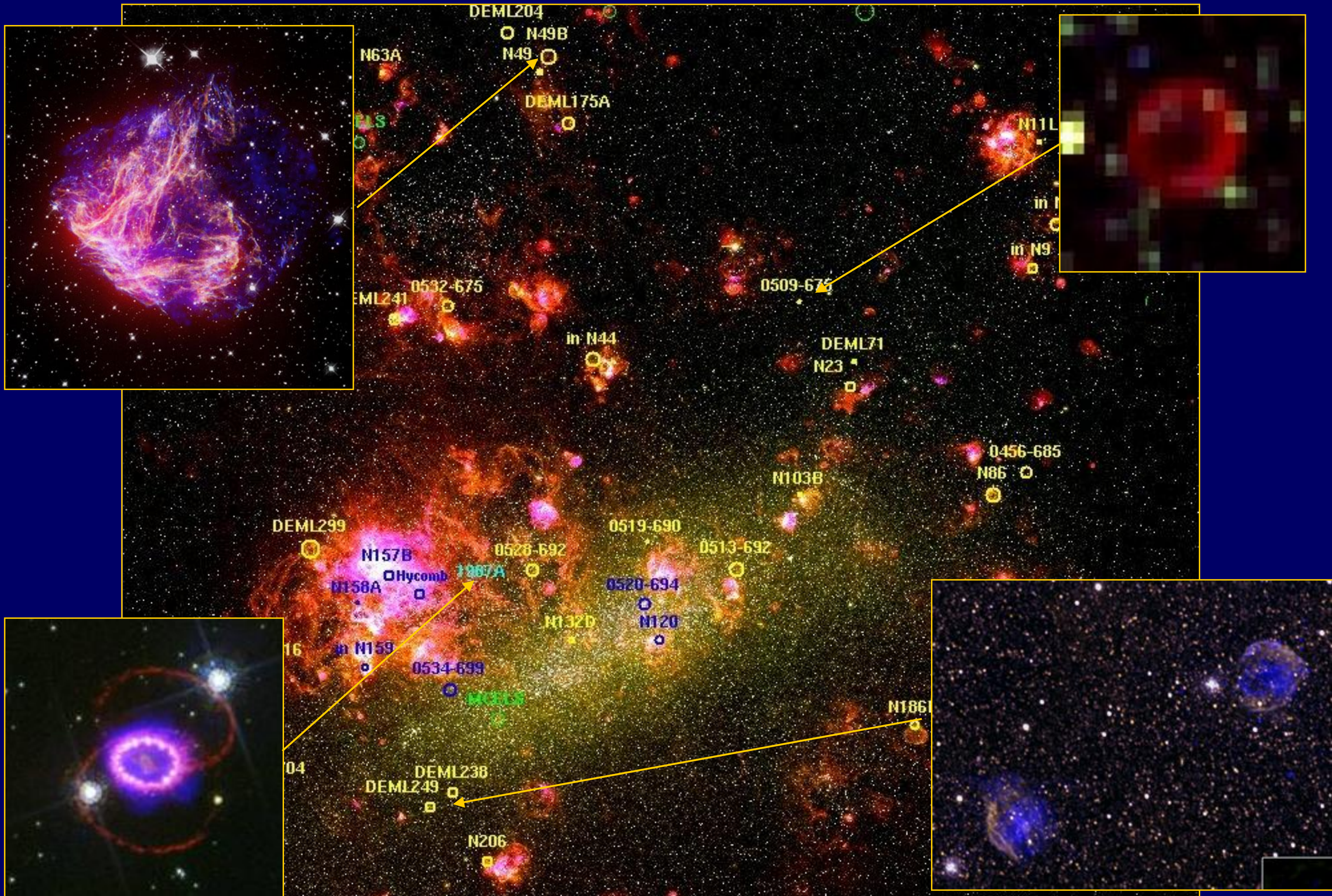
Maoz, Mannucci, et al. 2010

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

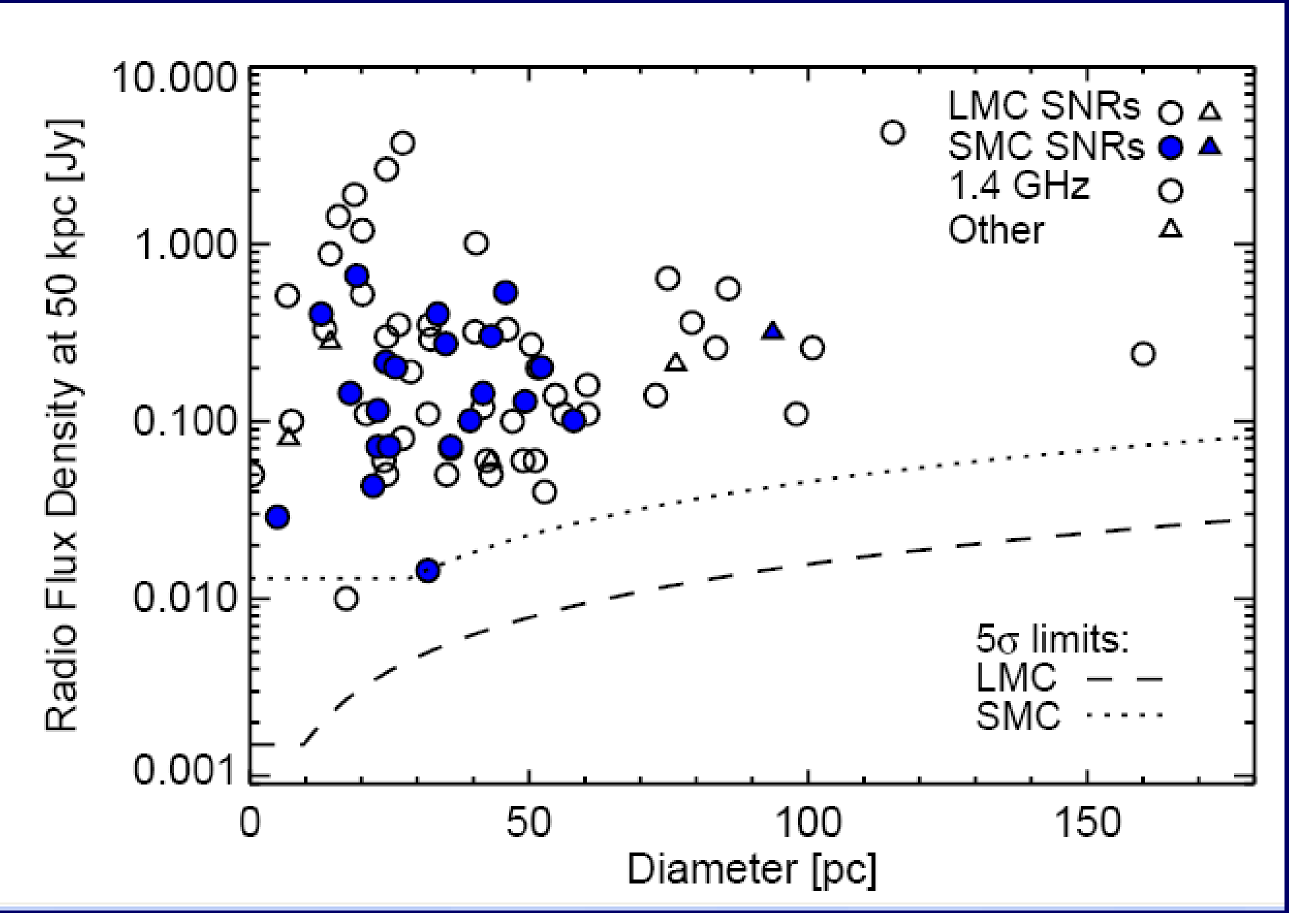
Similar method applied by Brandt+2010 to SDSS II, similar results.

How to recover the delay time distribution

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

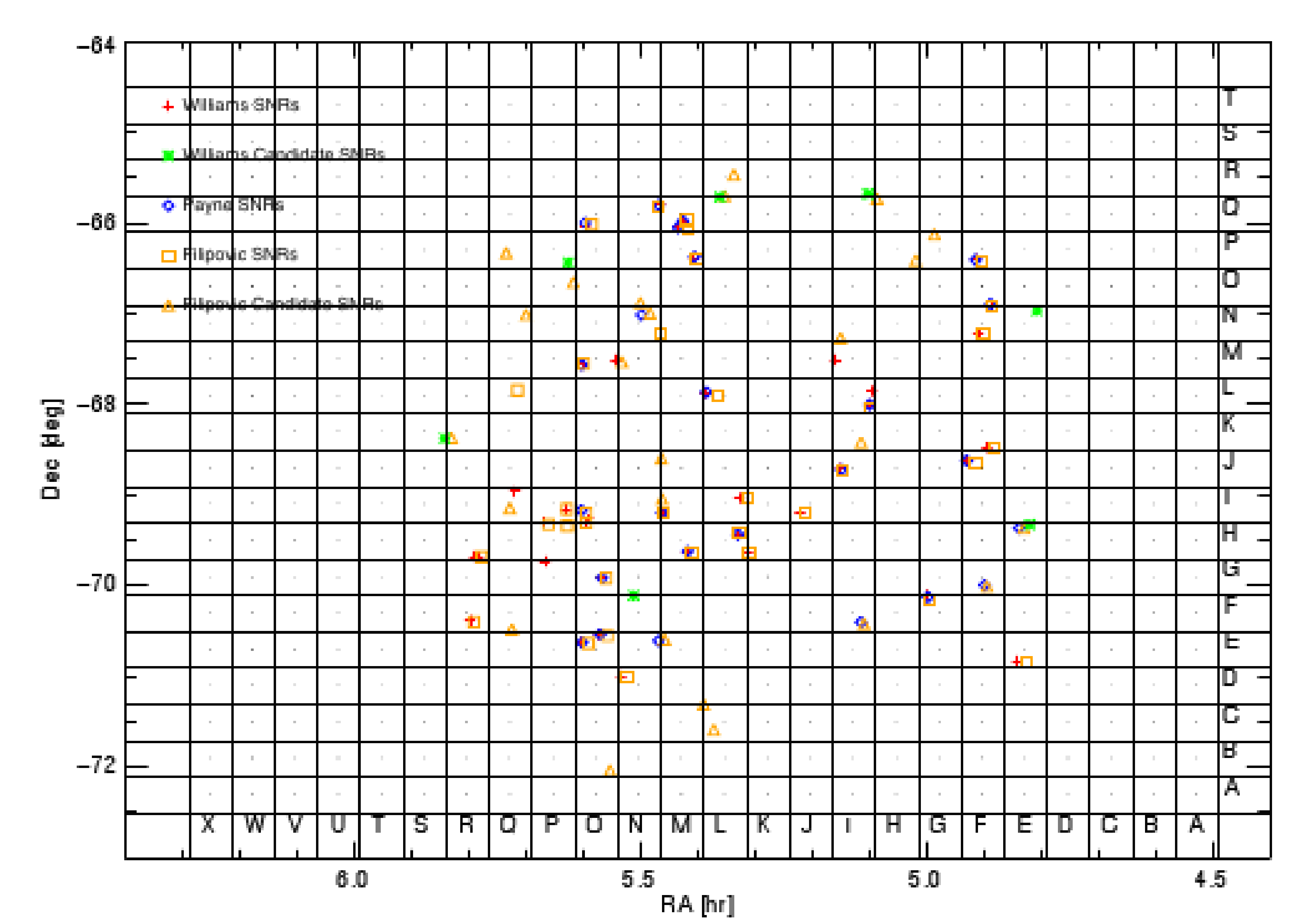

DEML204
N49B
N63A
N49
DEML175A
0532-675
in N44
DEML71
N23
0456-685
N86
N103B
DEML299
0519-690
0528-692
0513-692
N157B
Hycomb
N158A
0520-694
N132D
N120
0534-699
DEML238
DEML249
N206

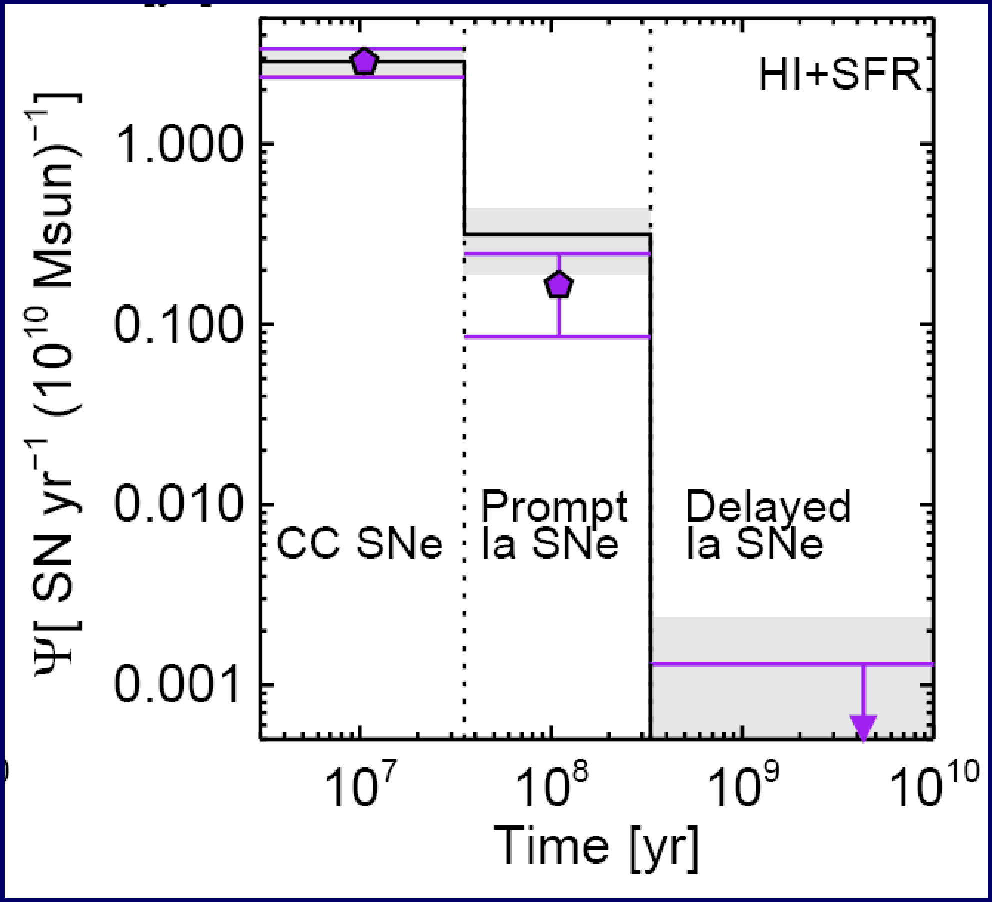
Sample of 77 SN remnants in the Clouds

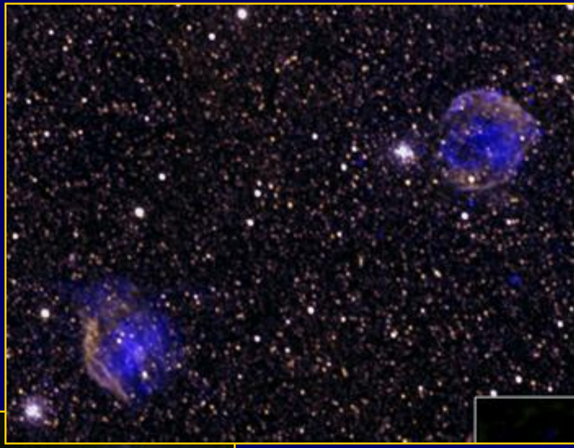


Badenes Maoz Draine 2010

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

How to recover the delay time distribution

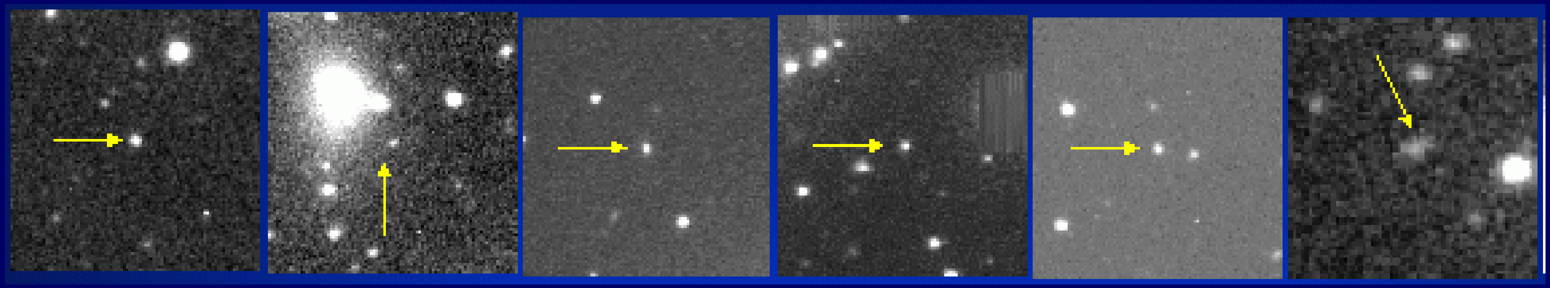
IV. SN rates in galaxy clusters

Cluster SN rate measurements

z~0.1:

Wise Obs. 1m

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

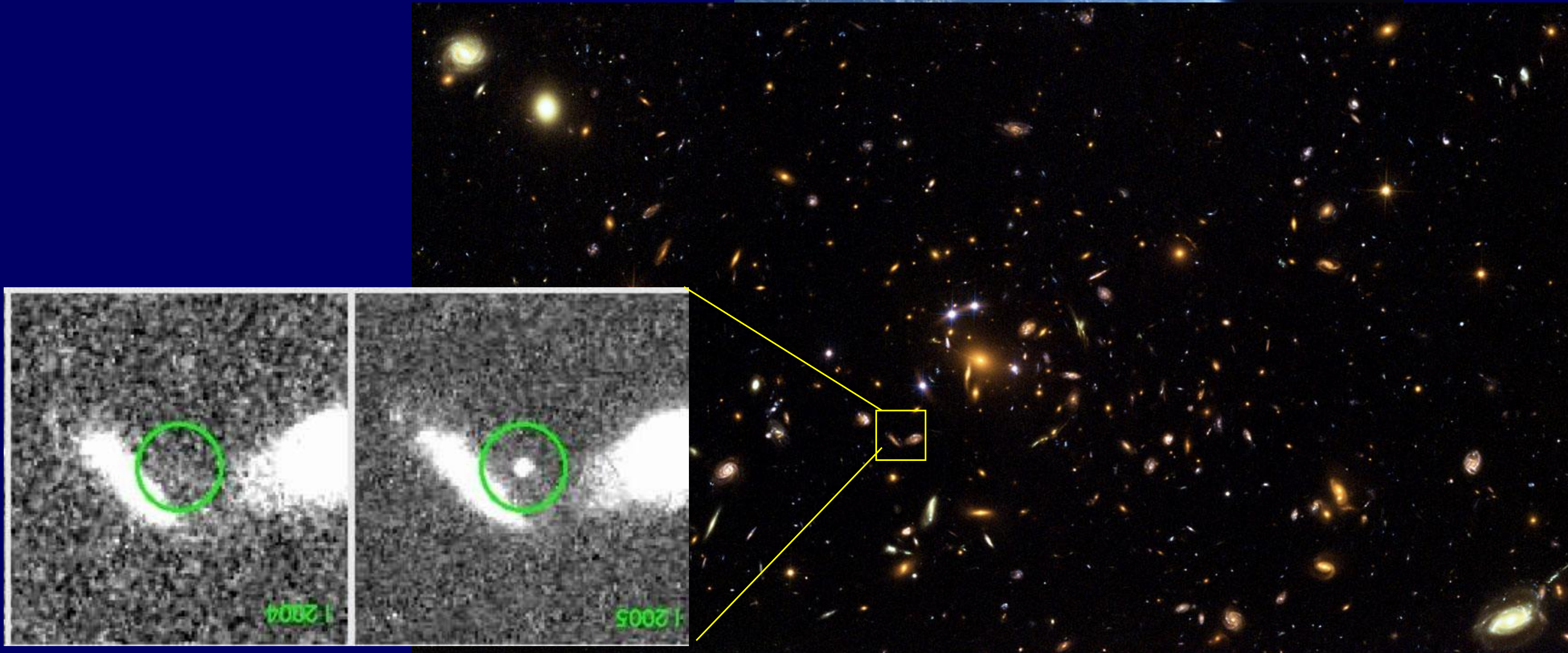


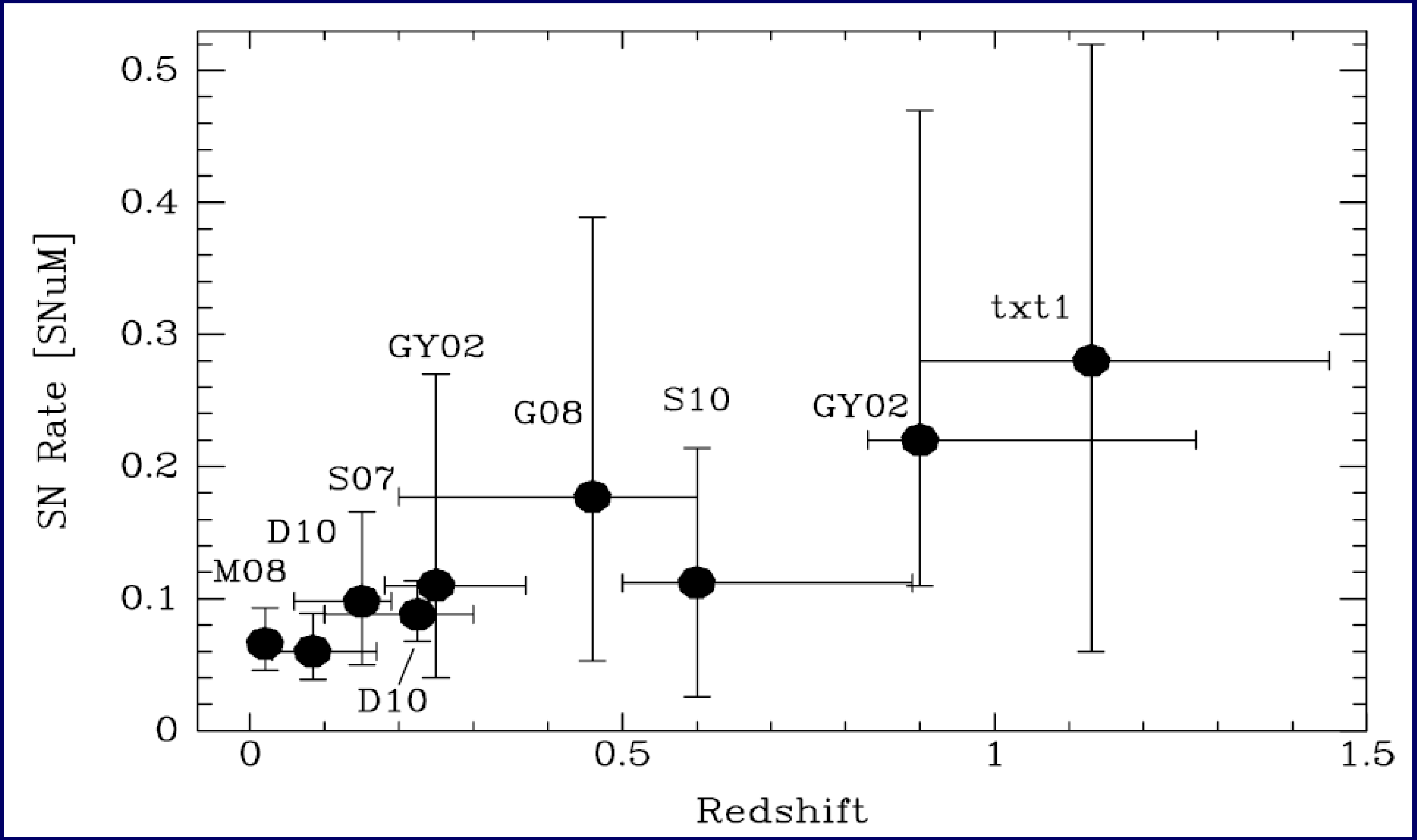
Cluster SN rate measurements

z~0.6:

HST

Sharon, Gal-Yam, et al. (2010)

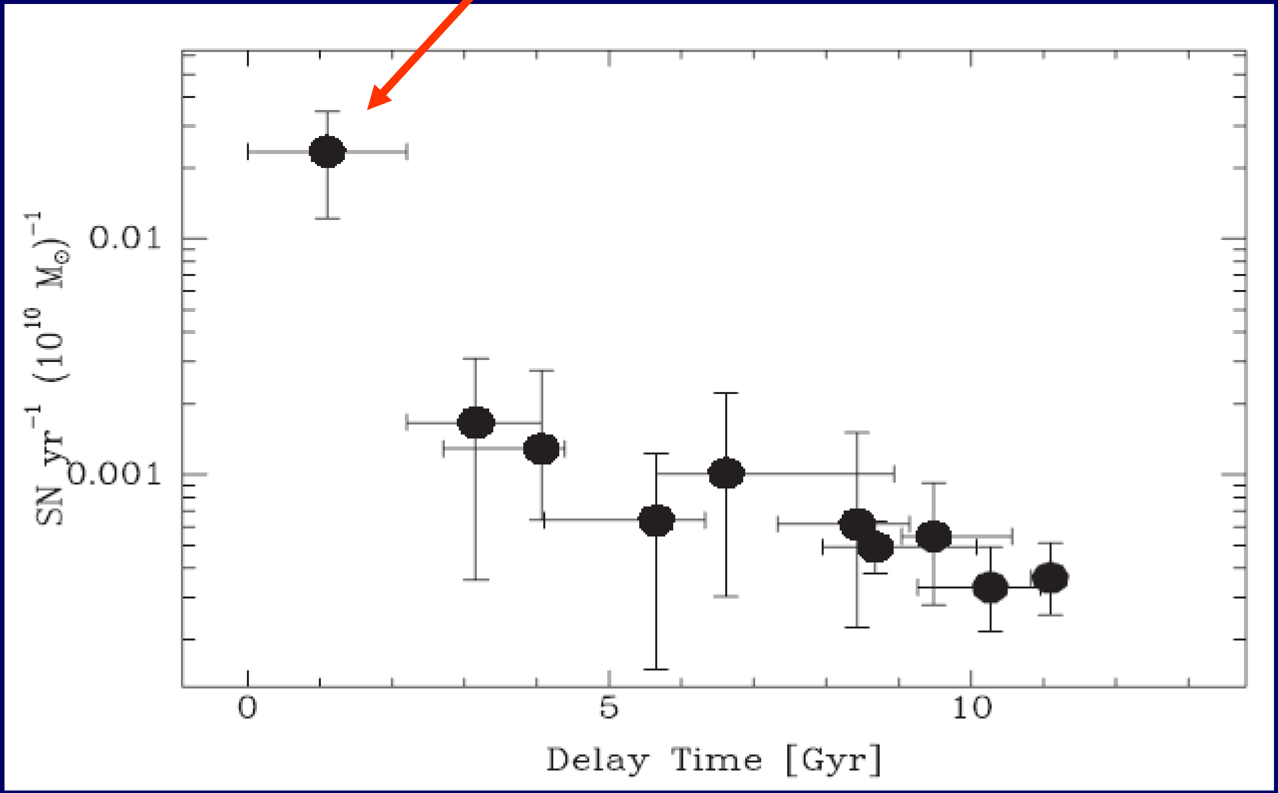




Maoz, Sharon, Gal-Yam (2010)

See also poster by K. Barbary

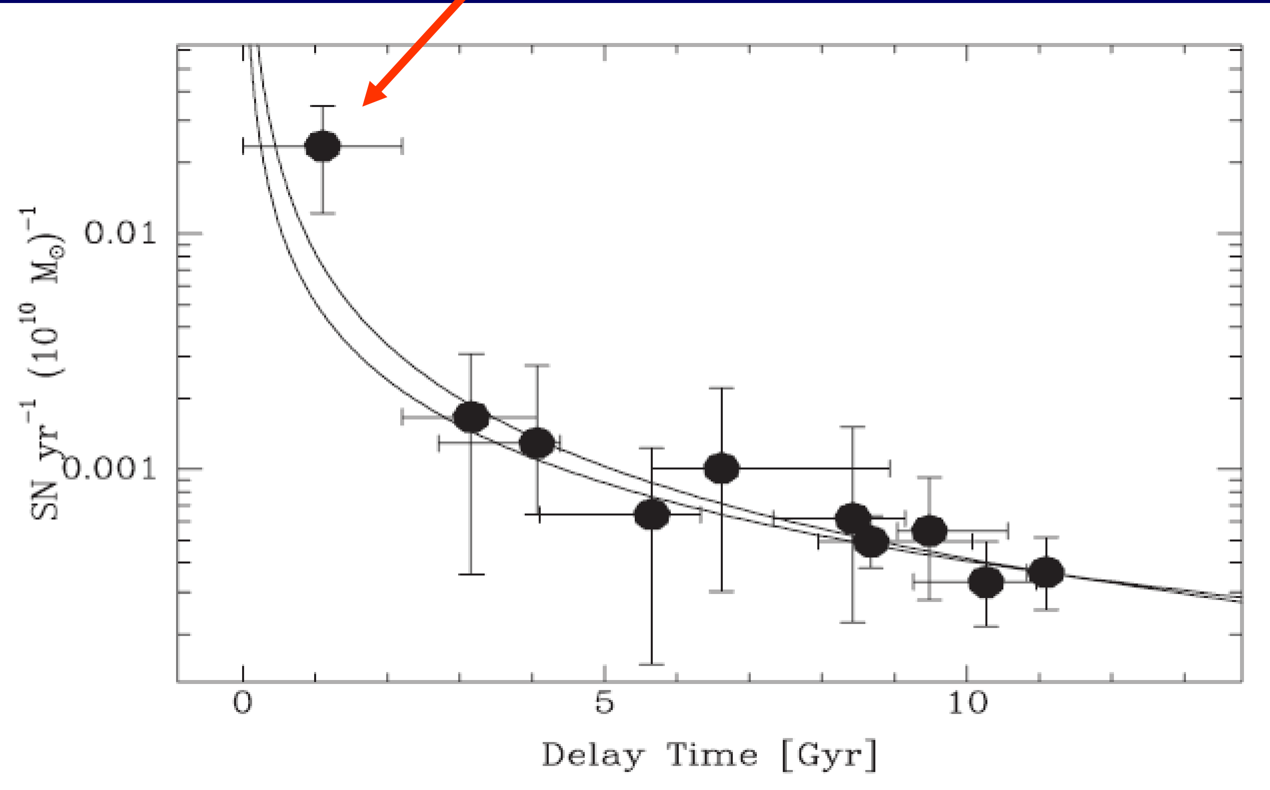
Time-integrated # of SNe-Ia must produce observed mass of Fe in clusters



Maoz, Sharon, Gal-Yam (2010)

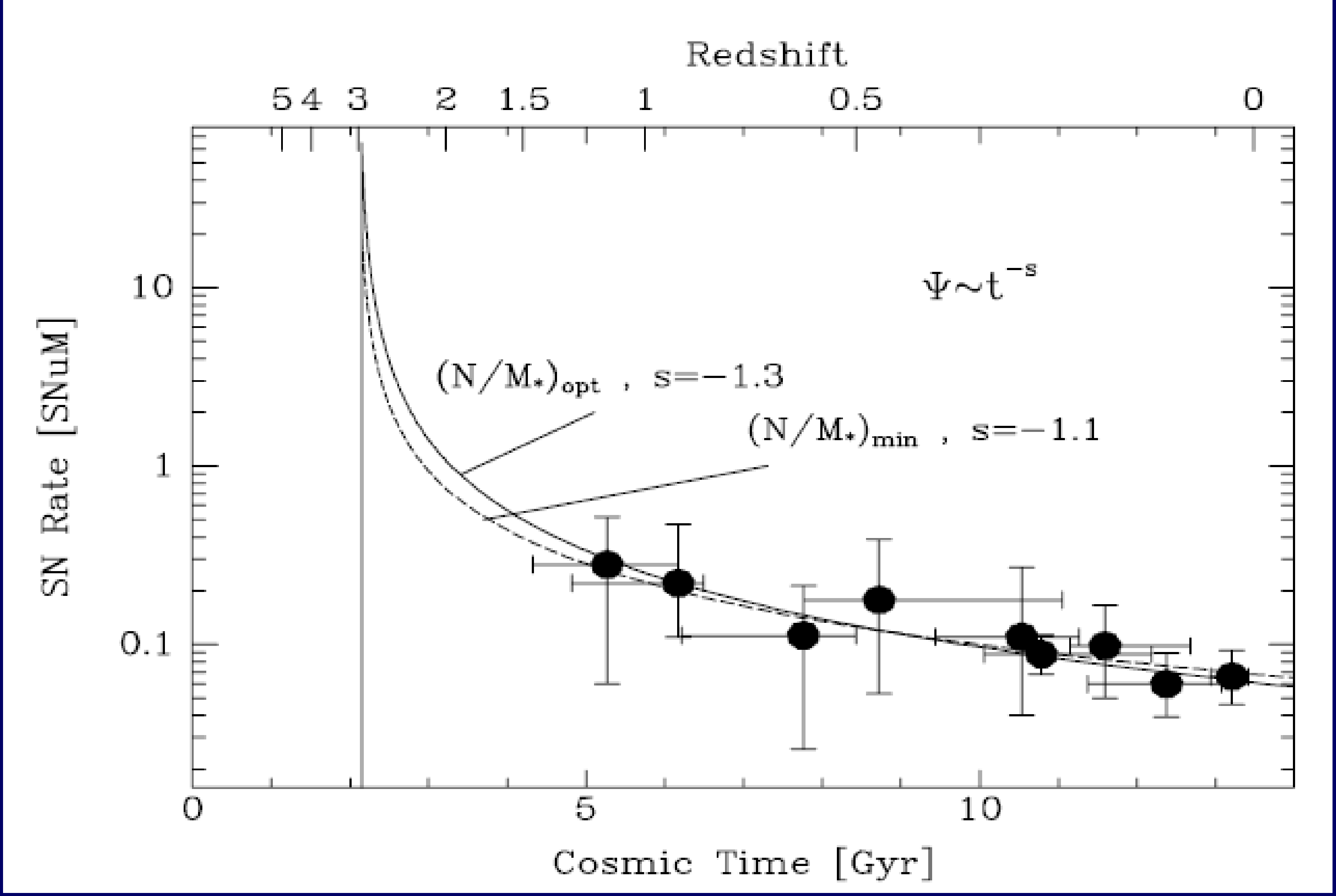
SN rates in galaxy clusters + iron/star mass ratio

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



Maoz, Sharon, Gal-Yam (2010)

Time until merger (gravitational wave losses):

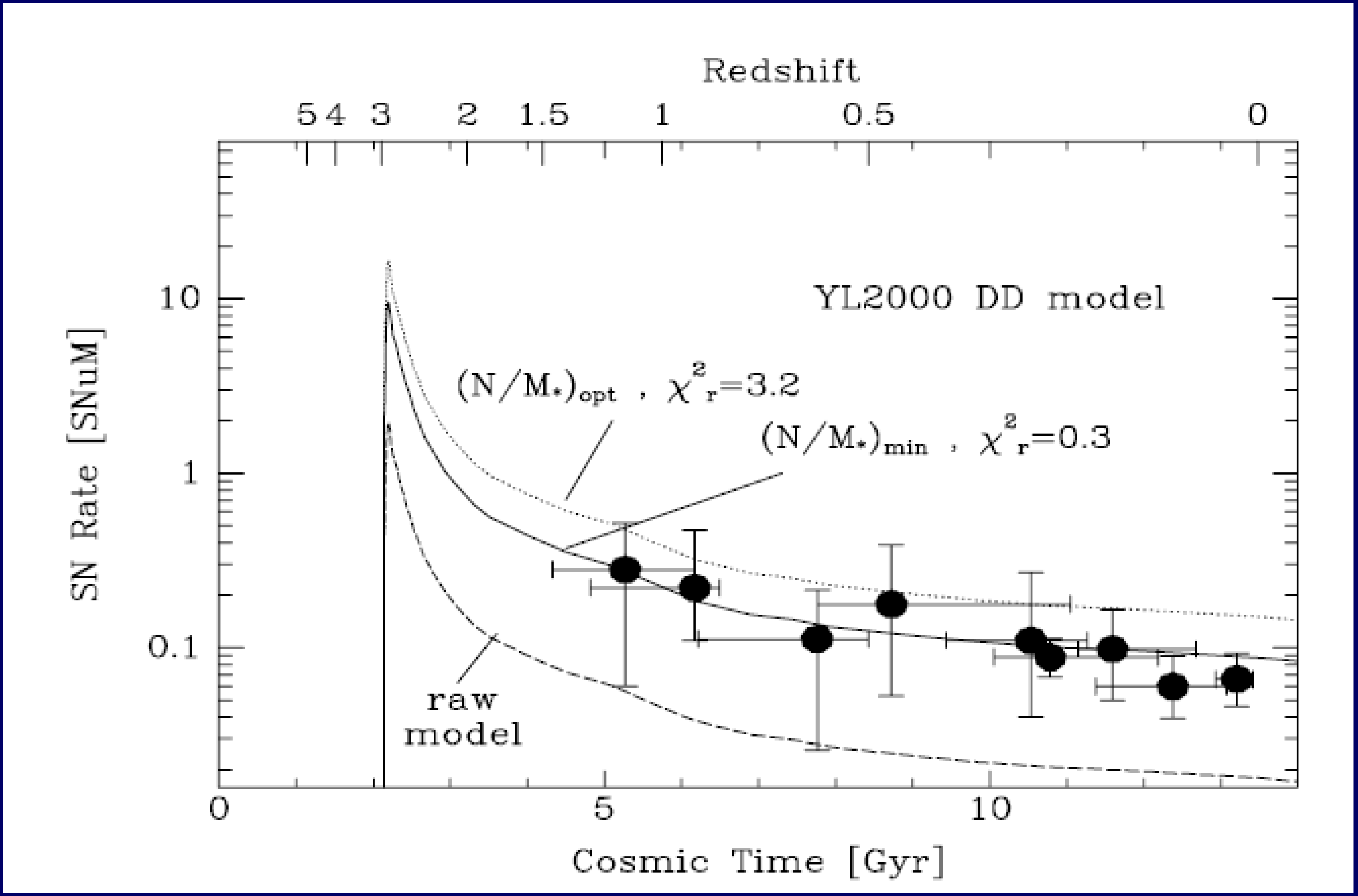
$$t \sim a^4.$$

If the separations are distributed as a power law

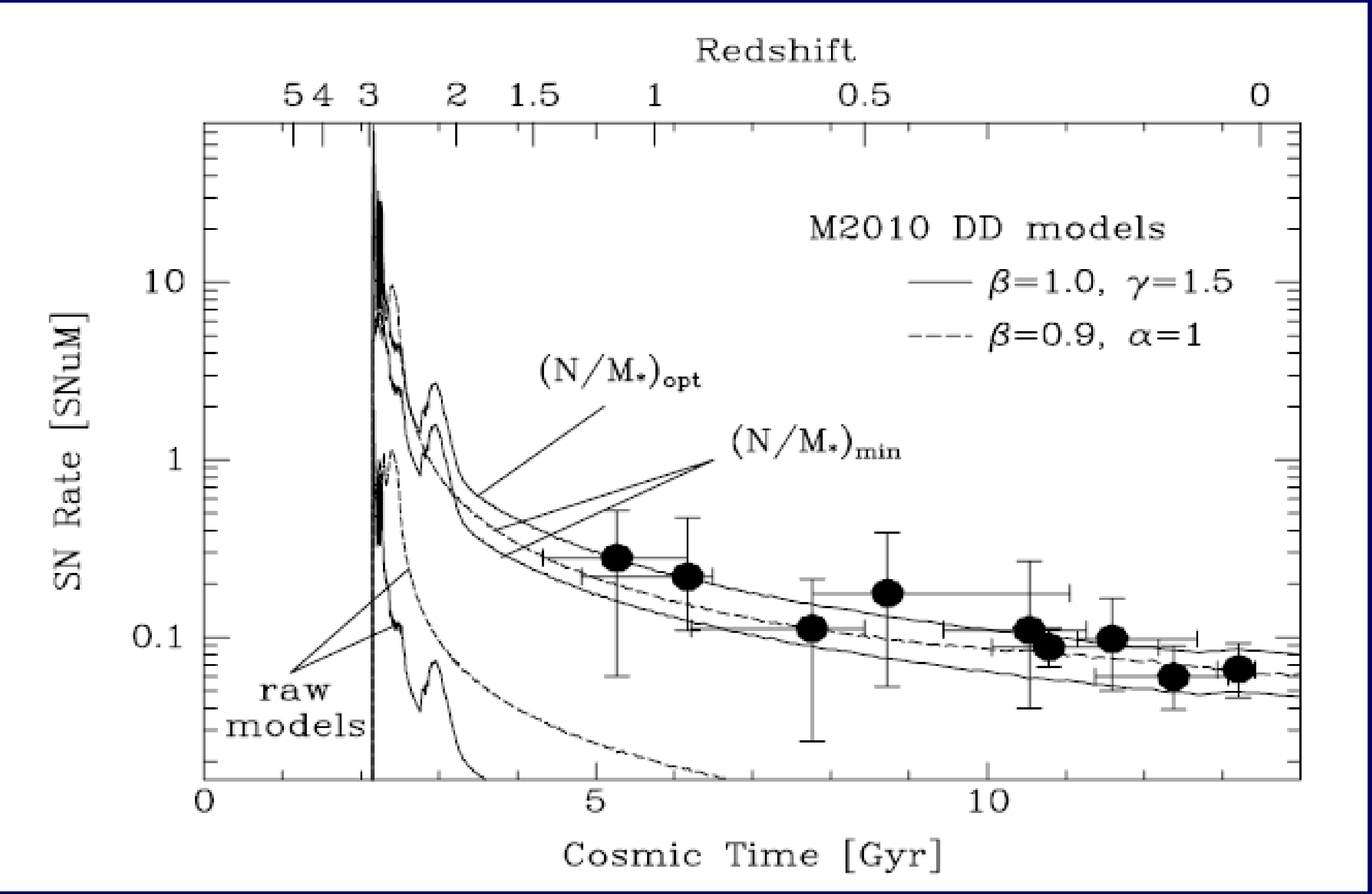
$$\frac{dN}{da} \sim a^{\epsilon},$$

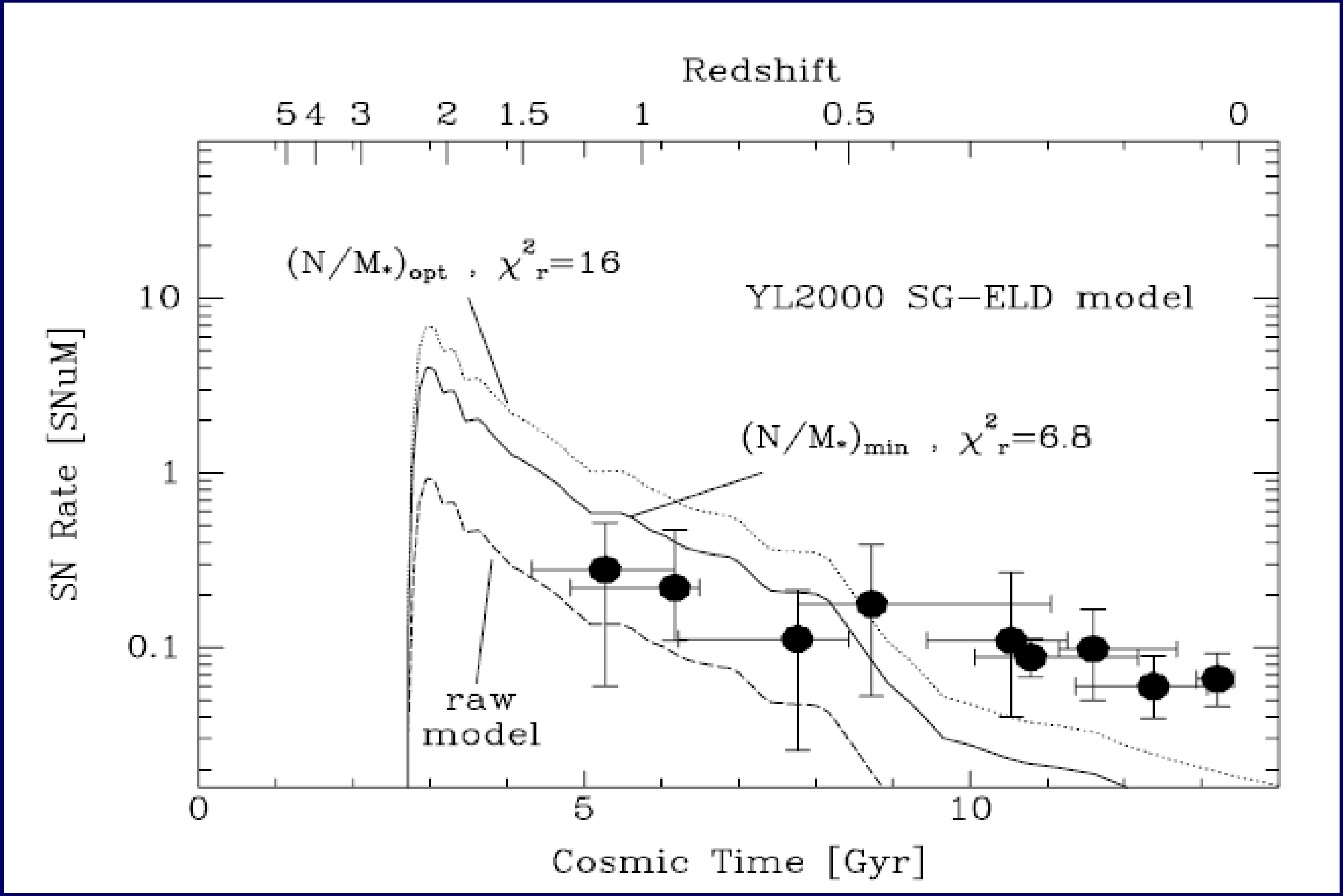
then the event rate will be

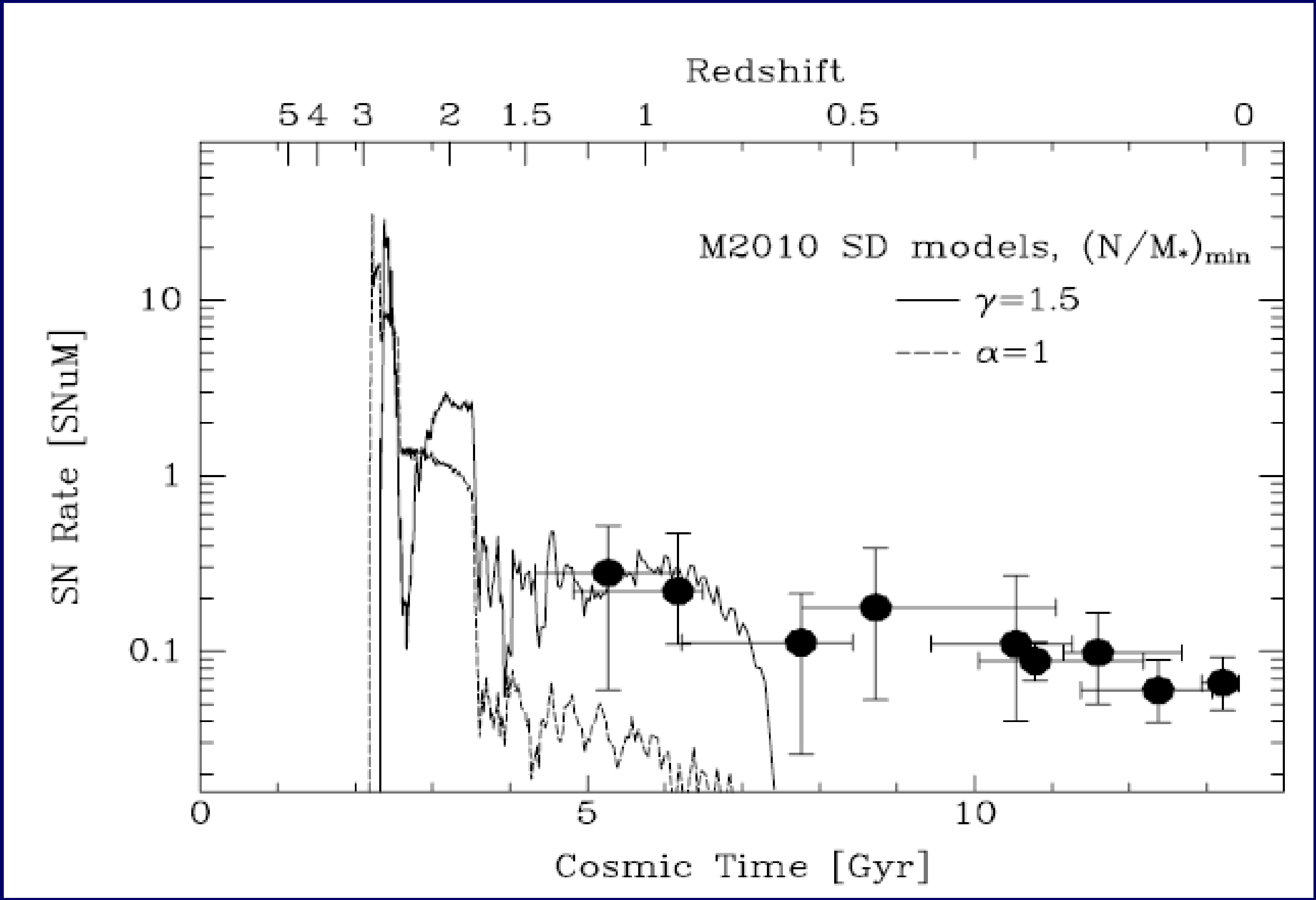
$$\frac{dN}{dt} = \frac{dN}{da}\frac{da}{dt} \sim t^{(\epsilon-3)/4}.$$

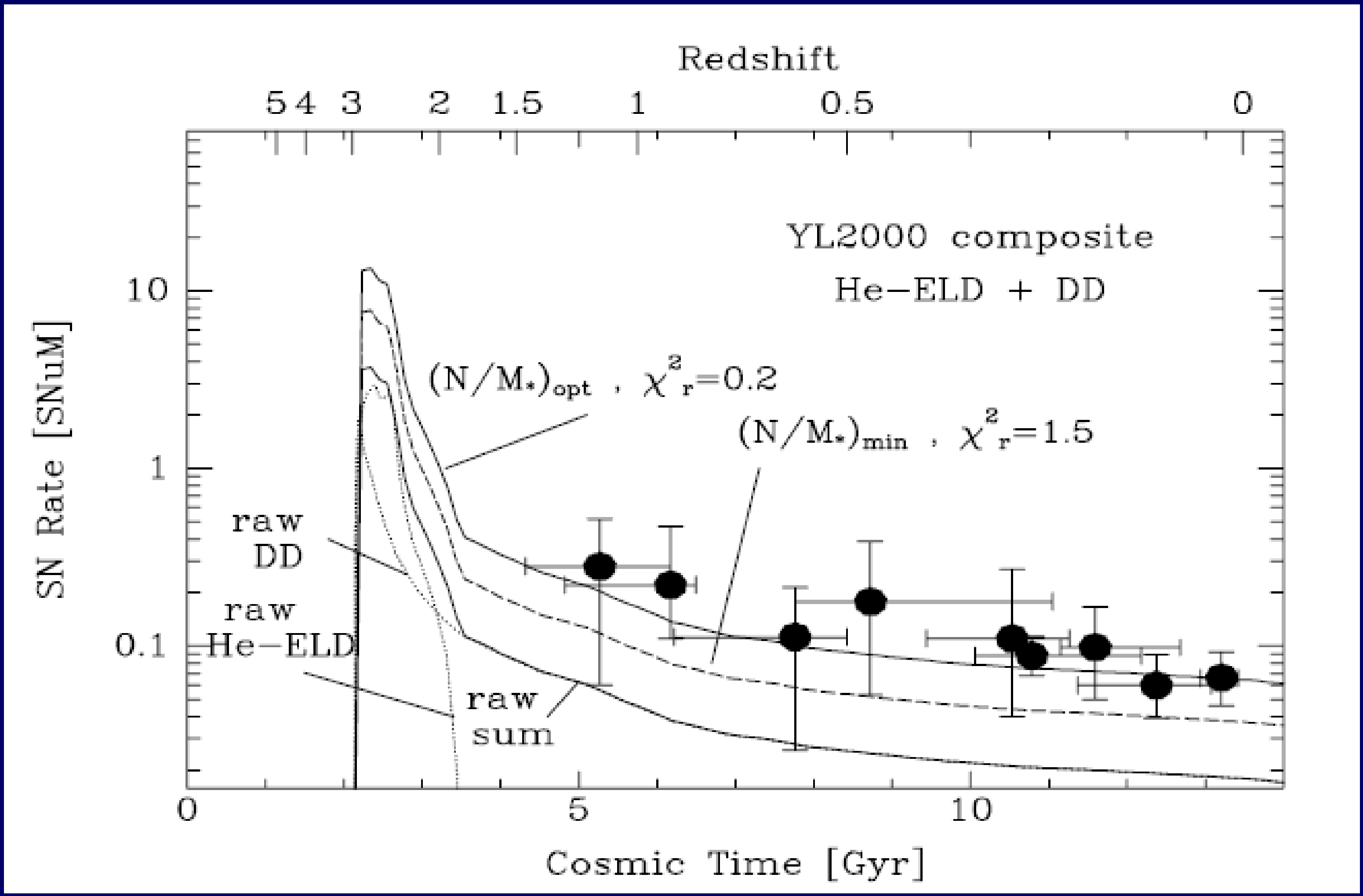


Redshift
5 4 3 2 1.5 1 0.5 0
YL2000 DD model
$(N/M_*)_{opt}$, χ^2_r=3.2
$(N/M_*)_{min}$, χ^2_r=0.3
raw model
SN Rate [SNuM]
10
1
0.1
0 5 10
Cosmic Time [Gyr]


Redshift
5 4 3 2 1.5 1 0.5 0
M2010 DD models
β=1.0, γ=1.5
β=0.9, α=1
(N/M*)opt
(N/M*)min
raw models
SN Rate [SNuM]
10
1
0.1
0 5 10
Cosmic Time [Gyr]


Redshift
5
4
3
2
1.5
1
0.5
0
(N/M*)opt , χ²r=16
YL2000 SG−ELD model
(N/M*)min , χ²r=6.8
raw
model
10
1
0.1
SN Rate [SNuM]
0
5
10
Cosmic Time [Gyr]


Redshift
5 4 3 2 1.5 1 0.5 0
M2010 SD models, (N/M*)min
γ=1.5
α=1
SN Rate [SNuM]
10
1
0.1
0
5
10
Cosmic Time [Gyr]

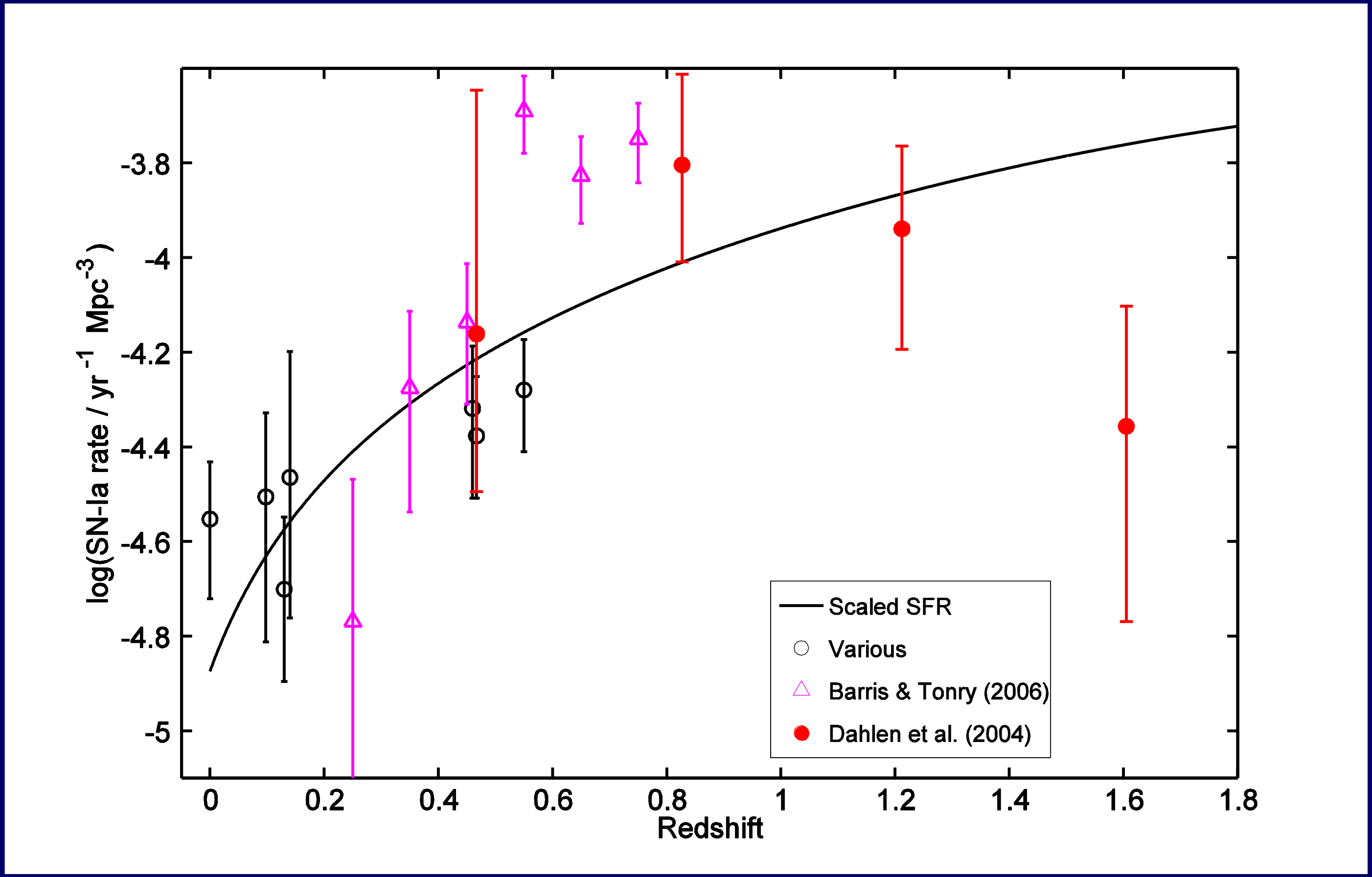


Redshift
5 4 3 2 1.5 1 0.5 0
YL2000 composite
He-ELD + DD
(N/M*)opt , χ²r=0.2
(N/M*)min , χ²r=1.5
SN Rate [SNuM]
10
1
0.1
raw
DD
raw
He-ELD
raw
sum
0 5 10
Cosmic Time [Gyr]

How to recover the delay time distribution

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

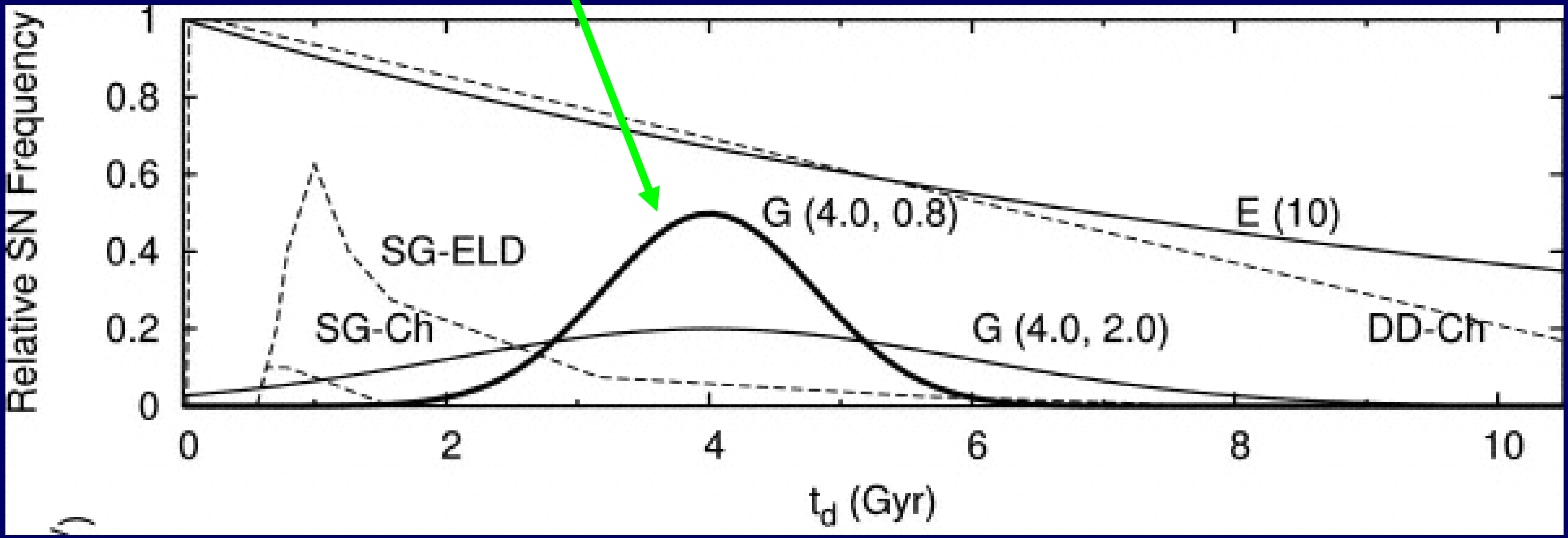
HST/ACS GOODS (~700 orbits) Riess, Dahlen, Strolger et al. 2004-2008, ~80 SNe, 46 SNe-Ia, 24 @ z>1



Peak in SN-Ia rate at z~0.8 implies $\tau > 3$ Gyr; inconsistent with other DTD estimates.

GOODS: no prompt, no delayed, only “intermediate” (4Gyr) SNe Ia

D(t)



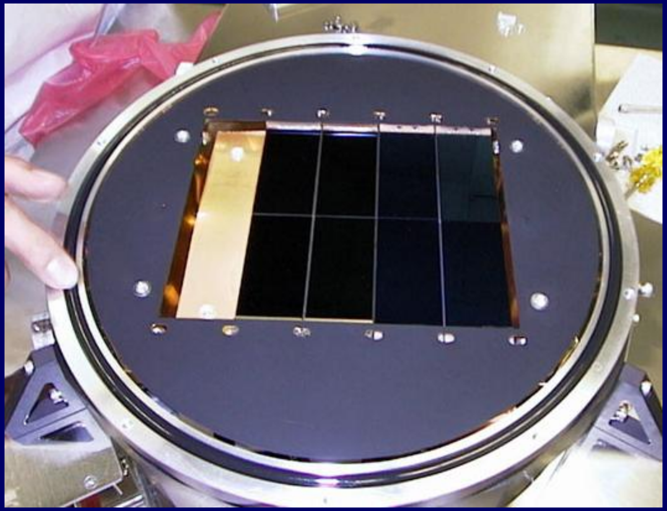
t

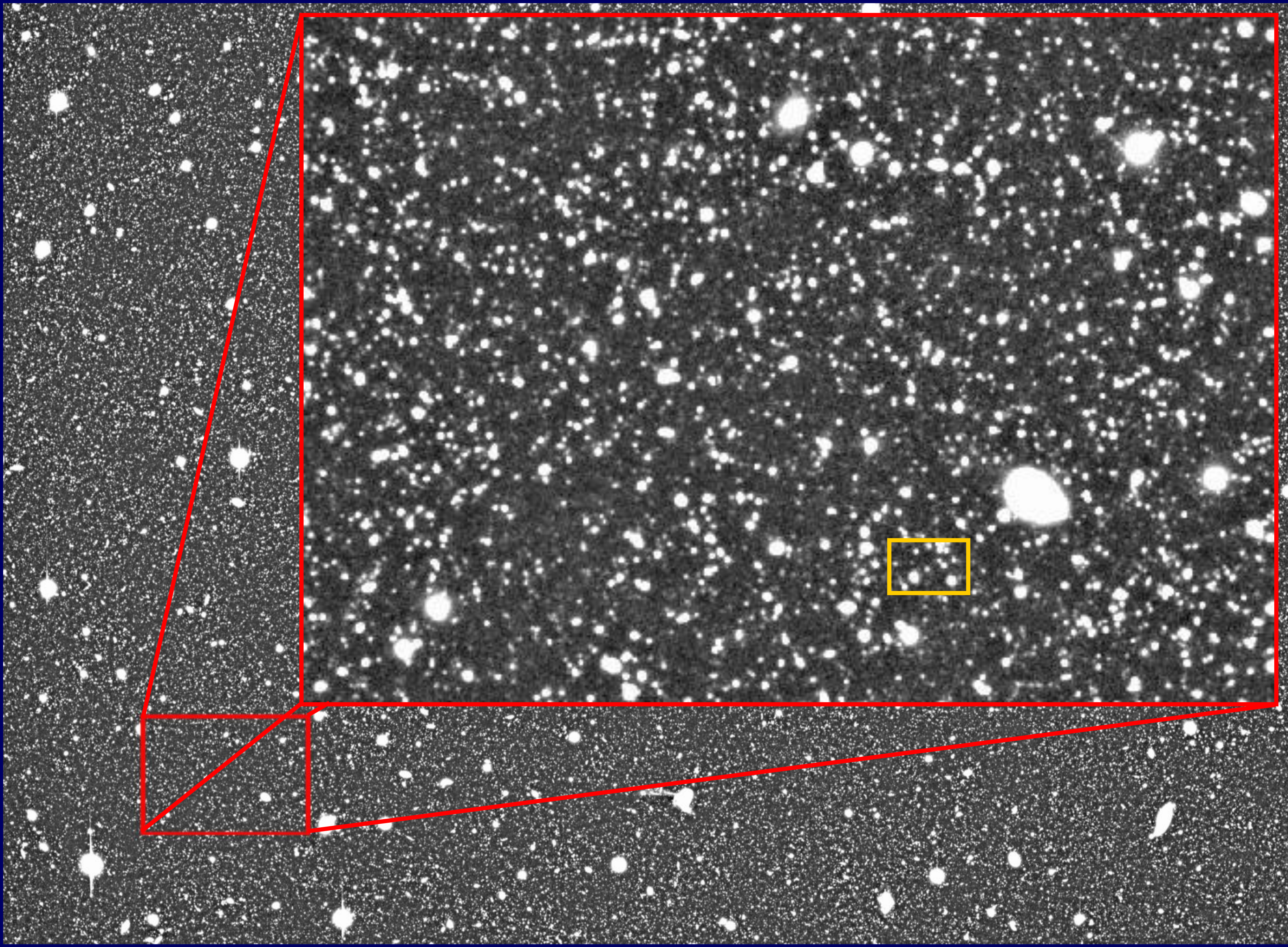
Strolger et al. 2004

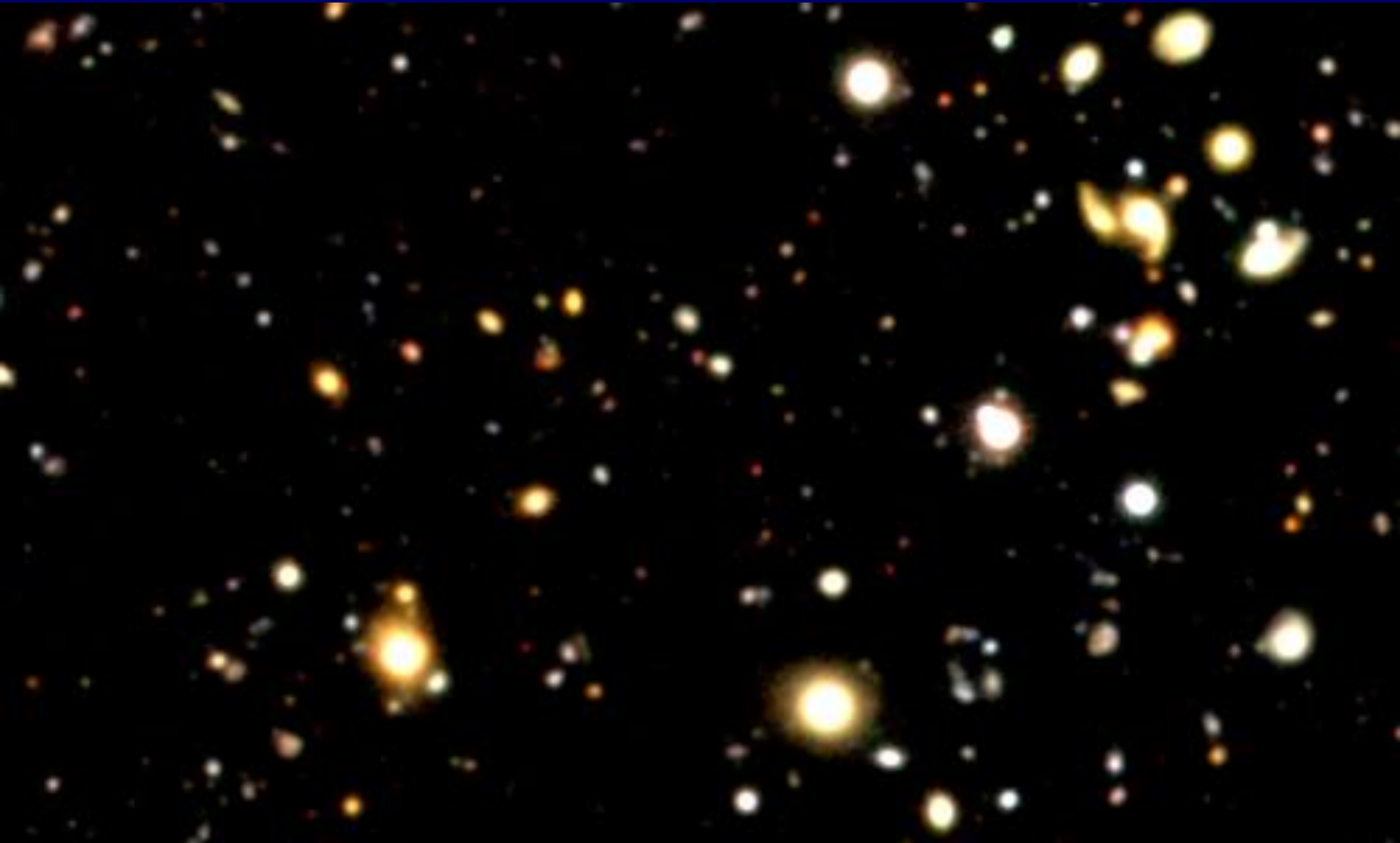
High-z SN rates in the Subaru Deep Field

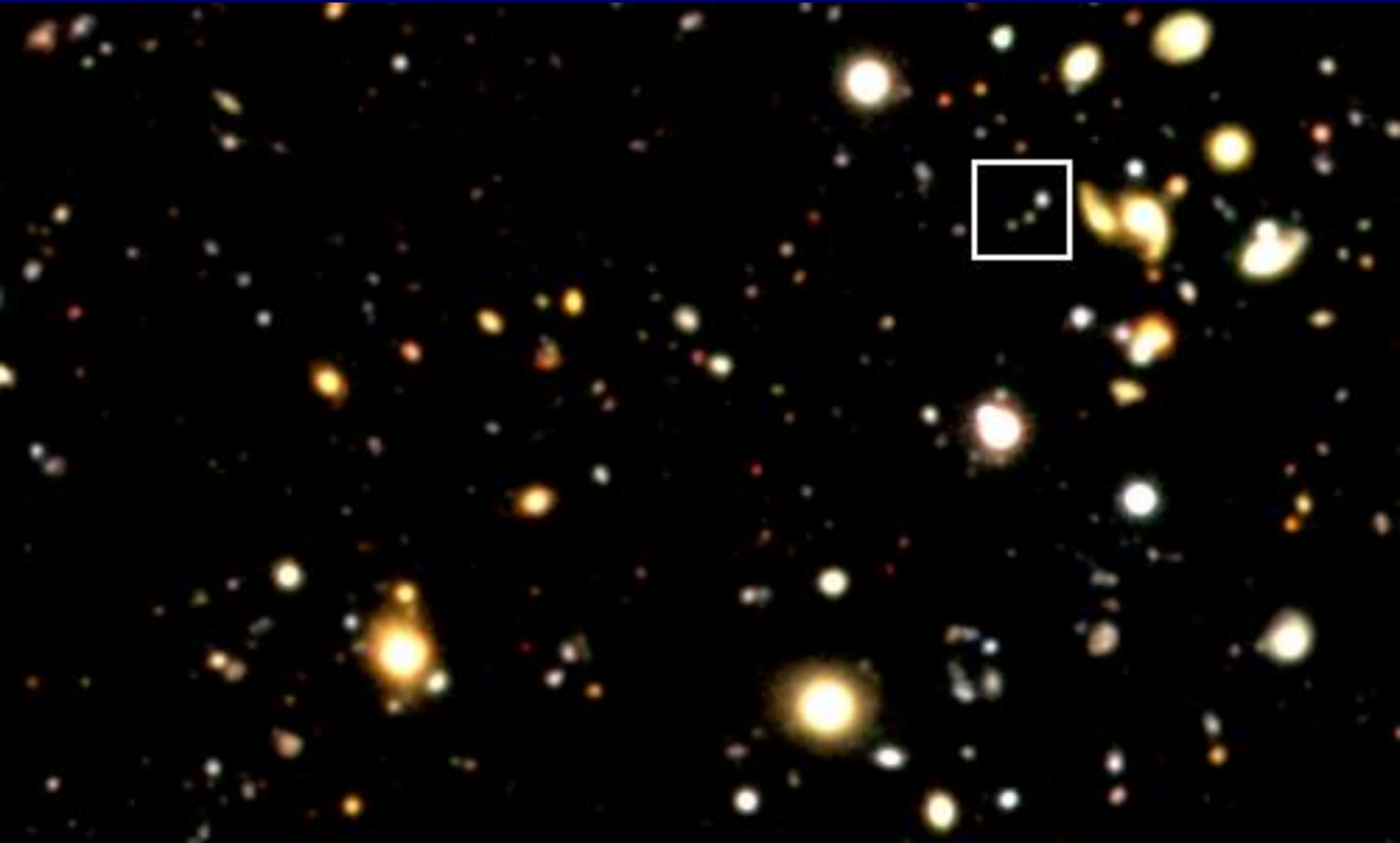
Poznanski et al 2007,
Graur et al., in prep.

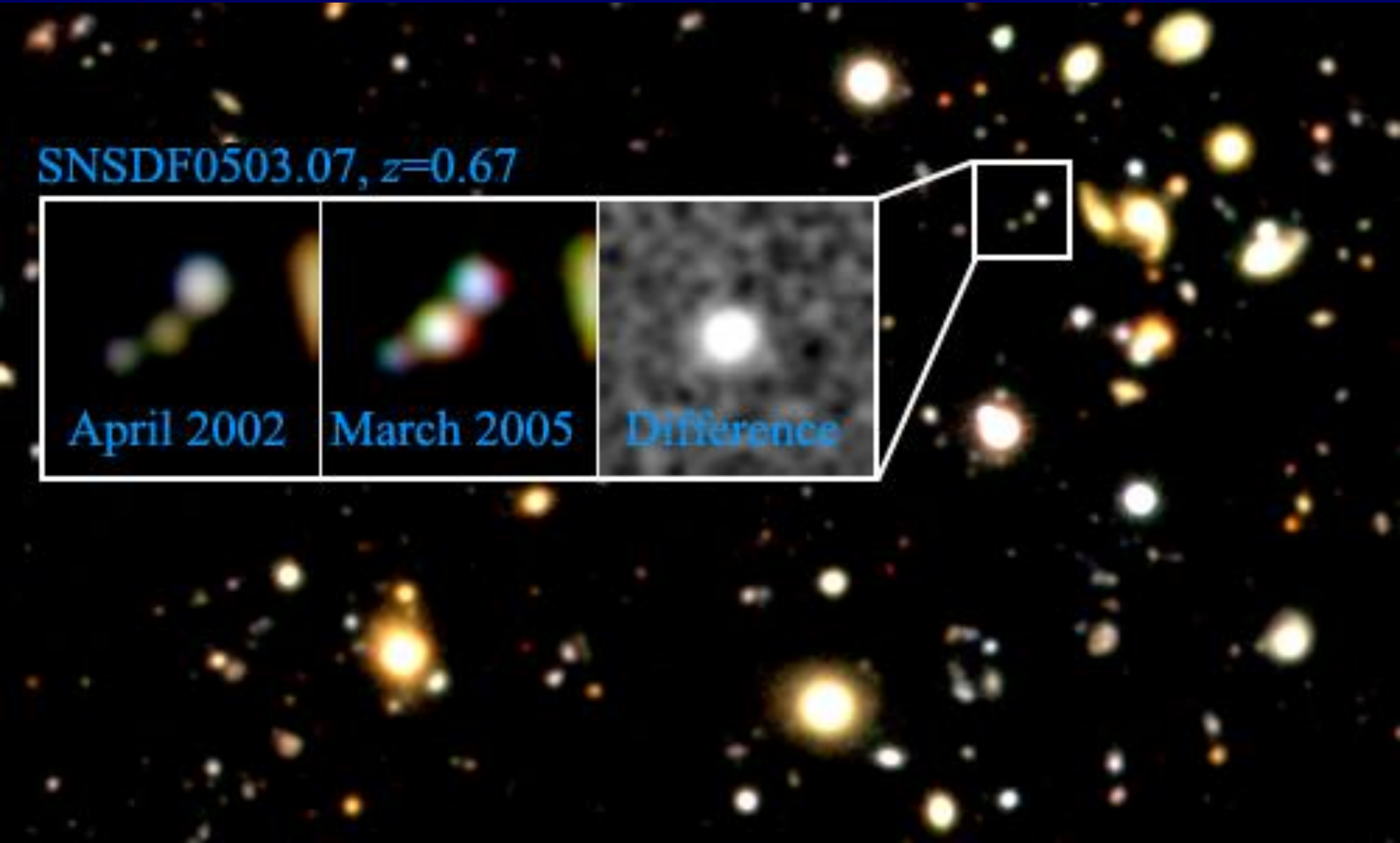
- 4x(2-night) runs
- Stare at the 0.25 deg^2 SDF:
  r, i ~ 27 mag z ~ 26 mag

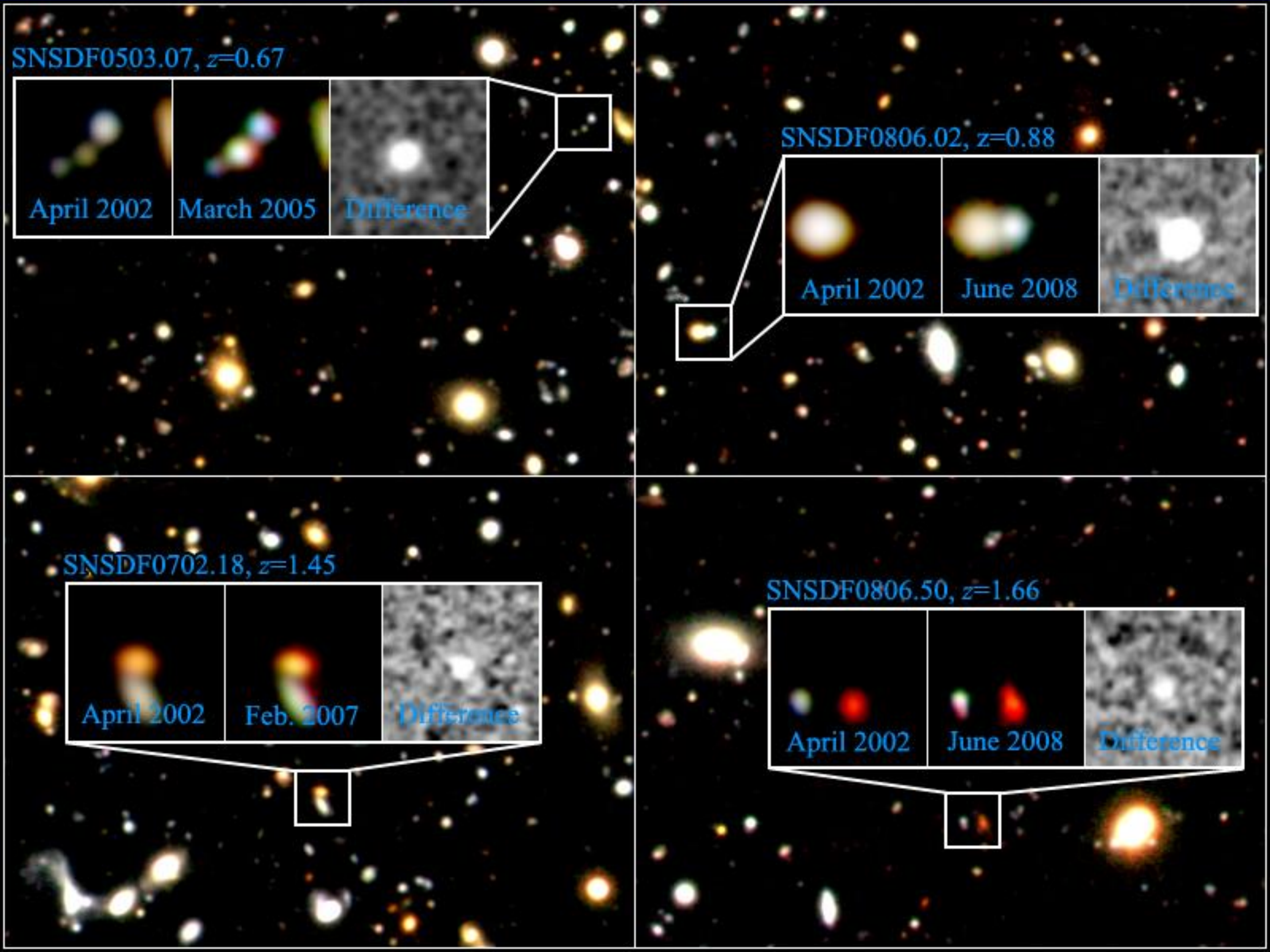









SNSDF0503.07, z=0.67
April 2002
March 2005
Difference

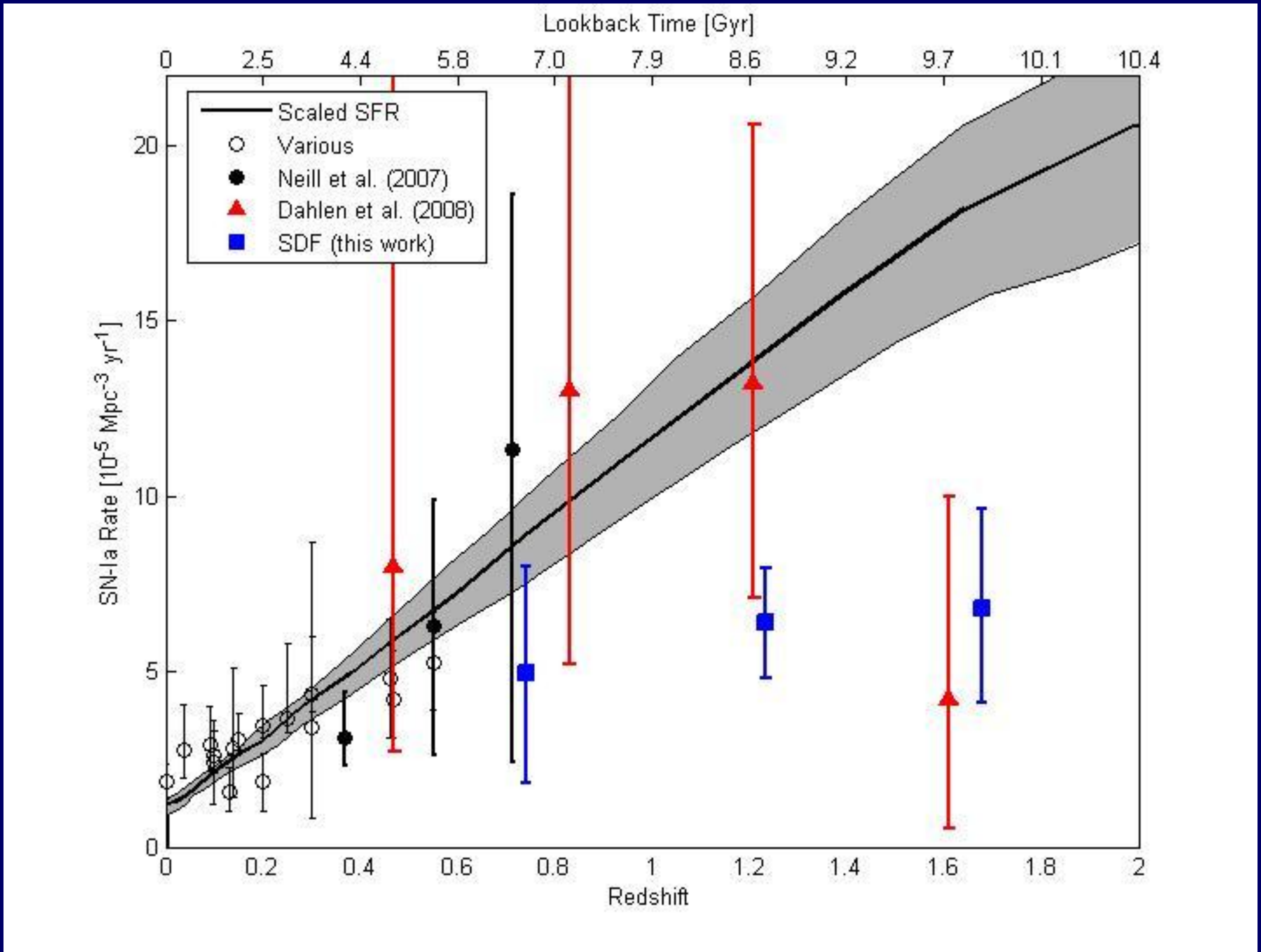


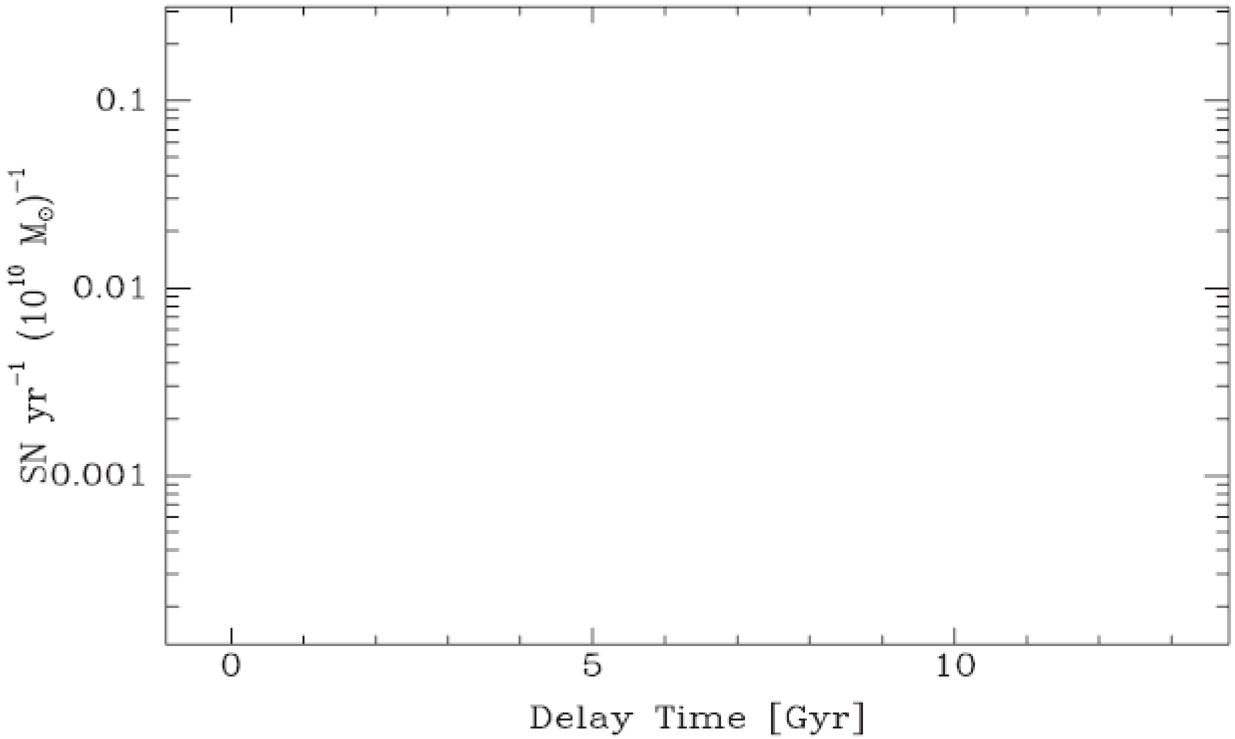
SNSDF0503.07, z=0.67
April 2002
March 2005
Difference
SNSDF0806.02, z=0.88
April 2002
June 2008
Difference
SNSDF0702.18, z=1.45
April 2002
Feb. 2007
Difference
SNSDF0806.50, z=1.66
April 2002
June 2008
Difference

Every epoch adds ~40 SNe:

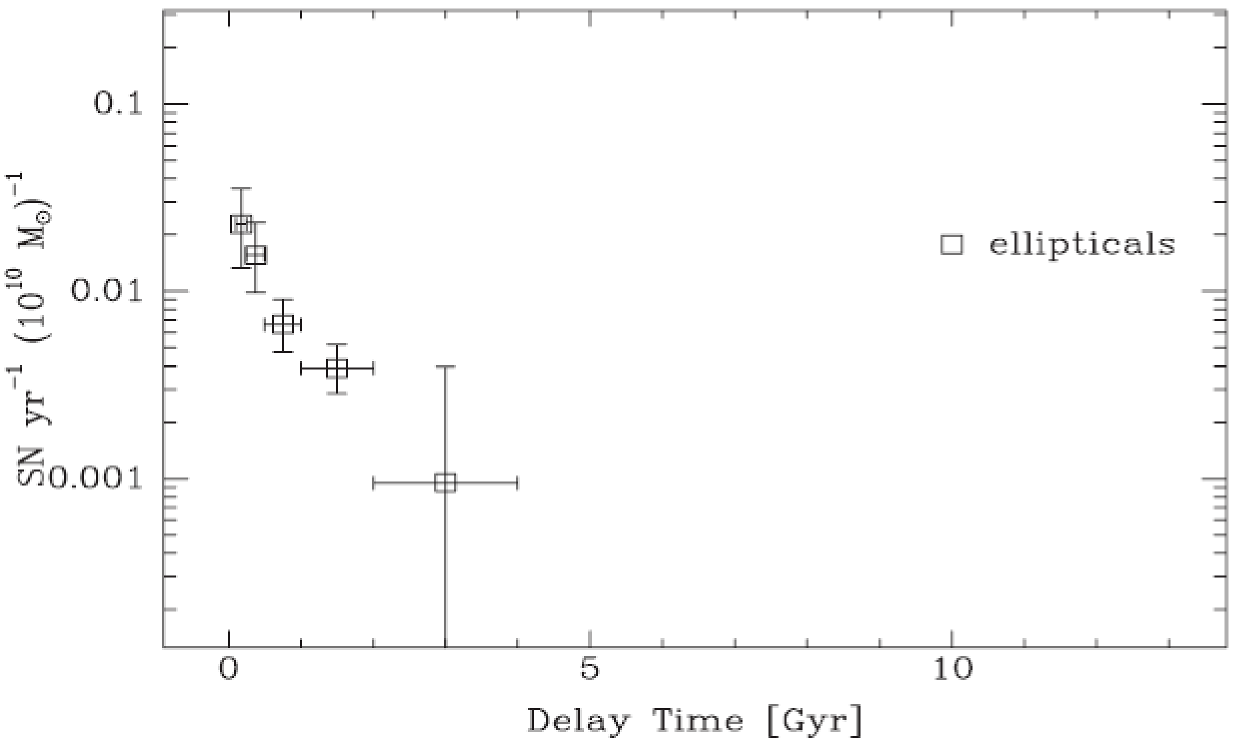
After 4 successful runs in 2005 - 2008: 150 SNe.

Graur et al., in prep.

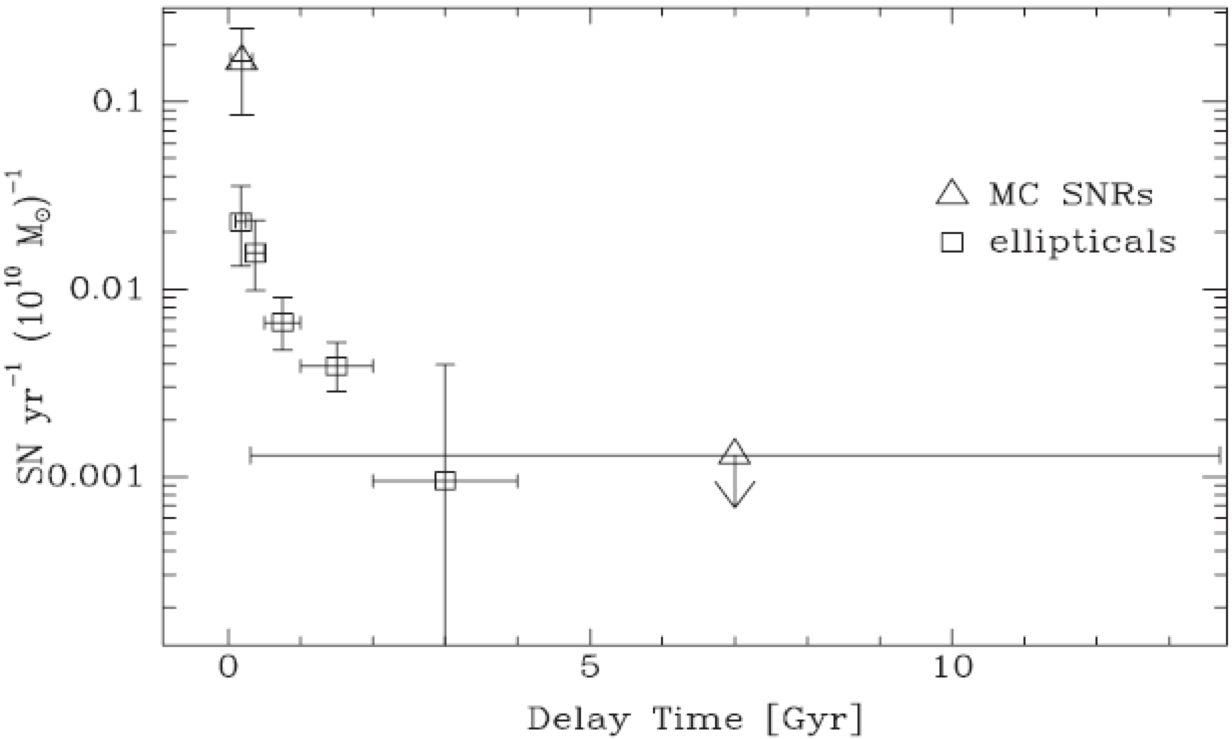




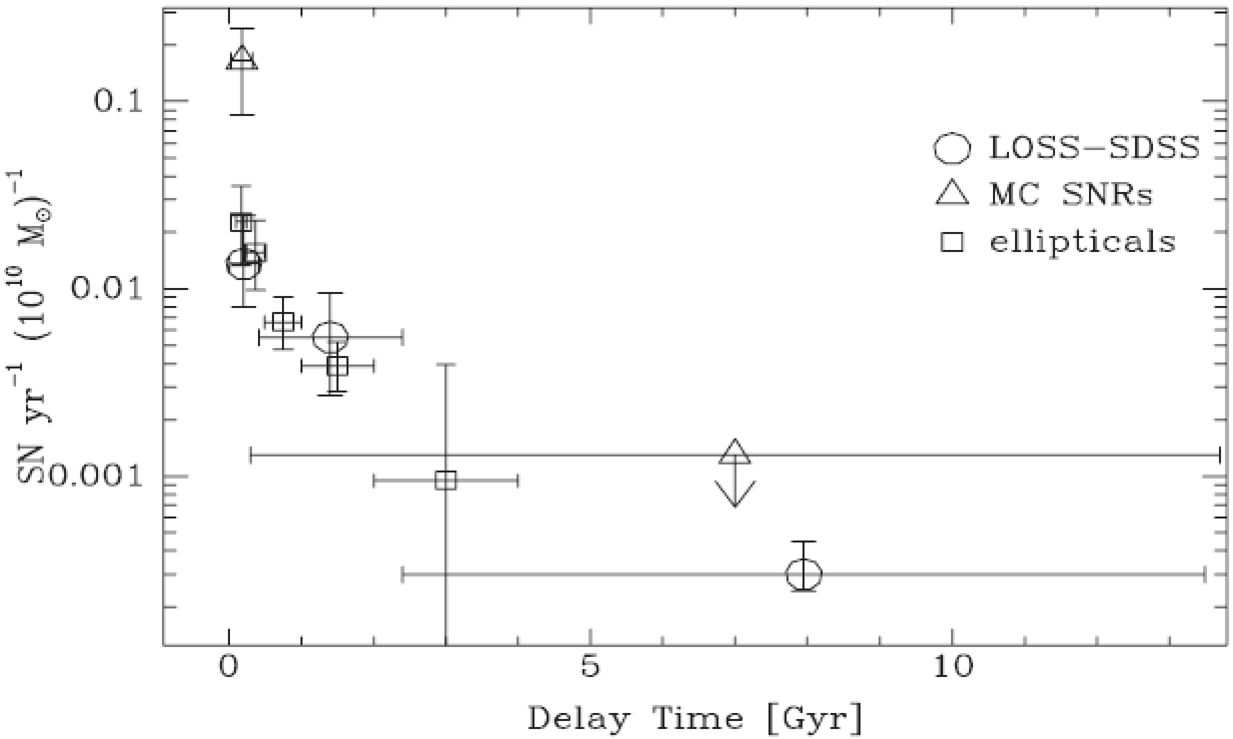
The DTD: a consistent picture emerging.



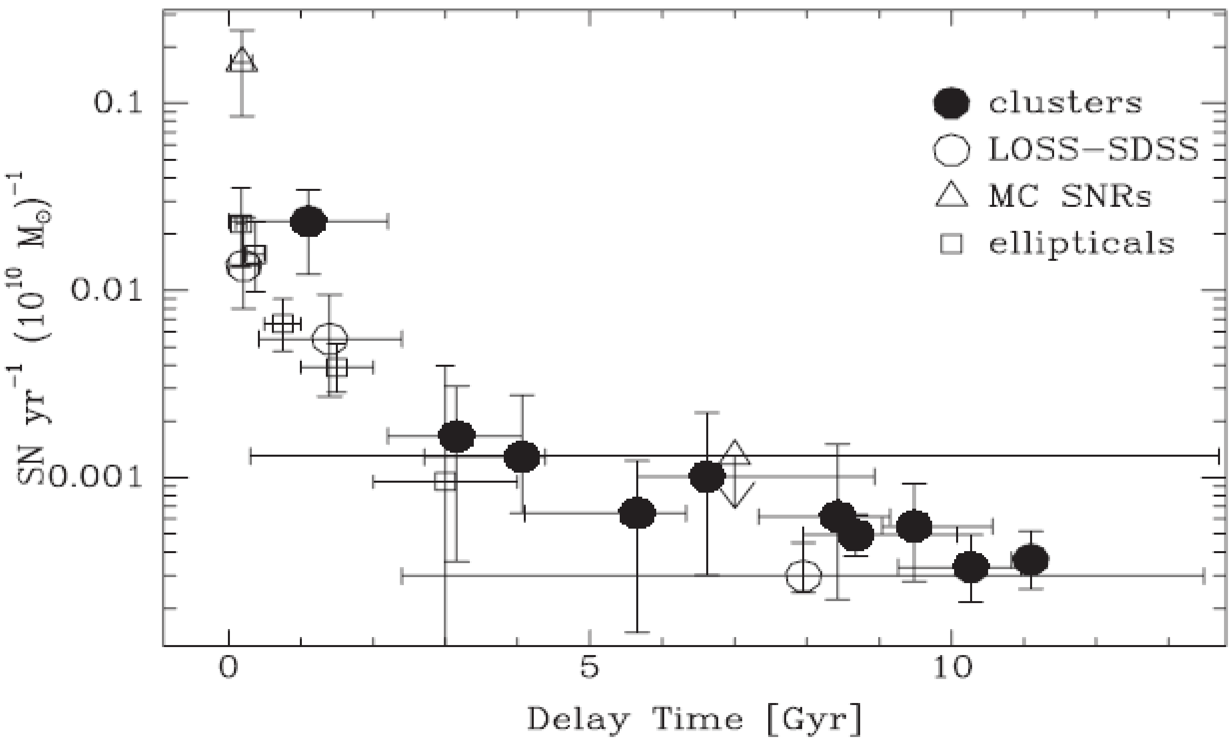
The DTD: a consistent picture emerging.



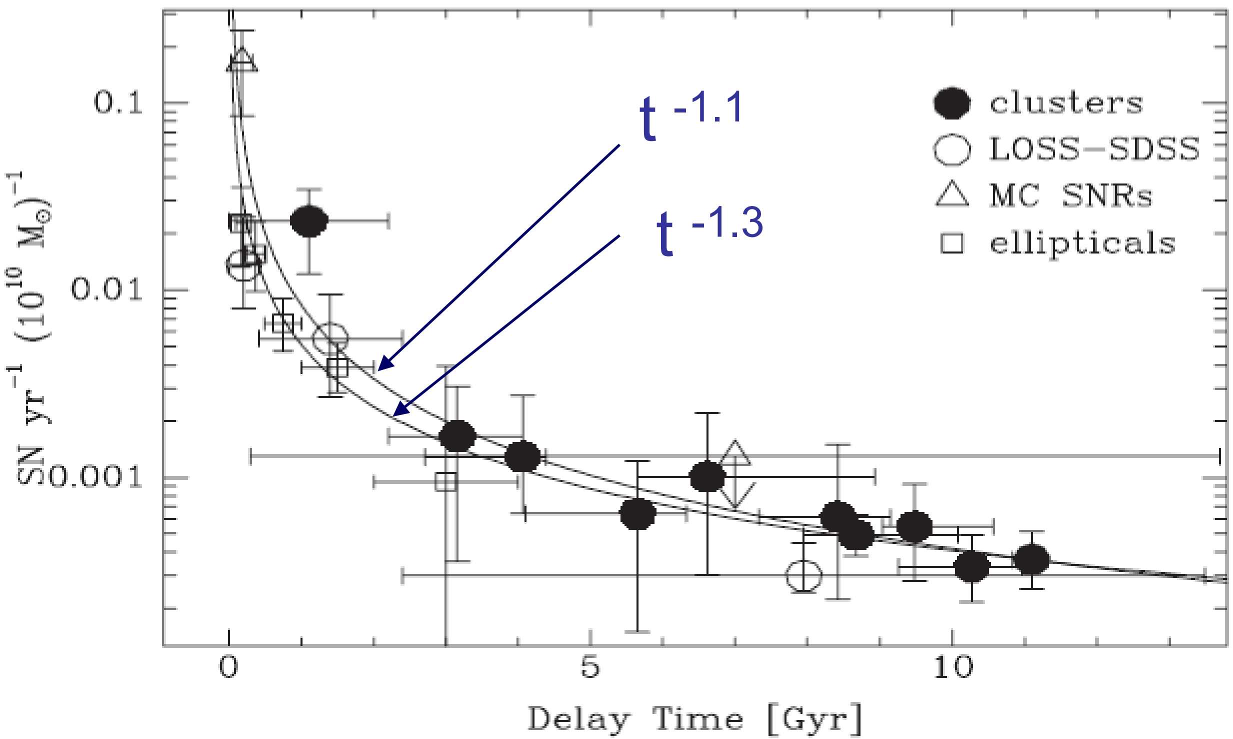
The DTD: a consistent picture emerging.



The DTD: a consistent picture emerging.



The DTD: a consistent picture emerging.



The DTD: a consistent picture emerging.

Summary:

Many different ways to try to get the delay function:

1. Traditional ways:

a. SN rates in populations of different mean ages

b. SN rate vs. cosmic time, compared to SFH

2. Novel ways:

a. SN rate in clusters vs. cosmic time

b. SN rate vs. SFHs in individual galaxies

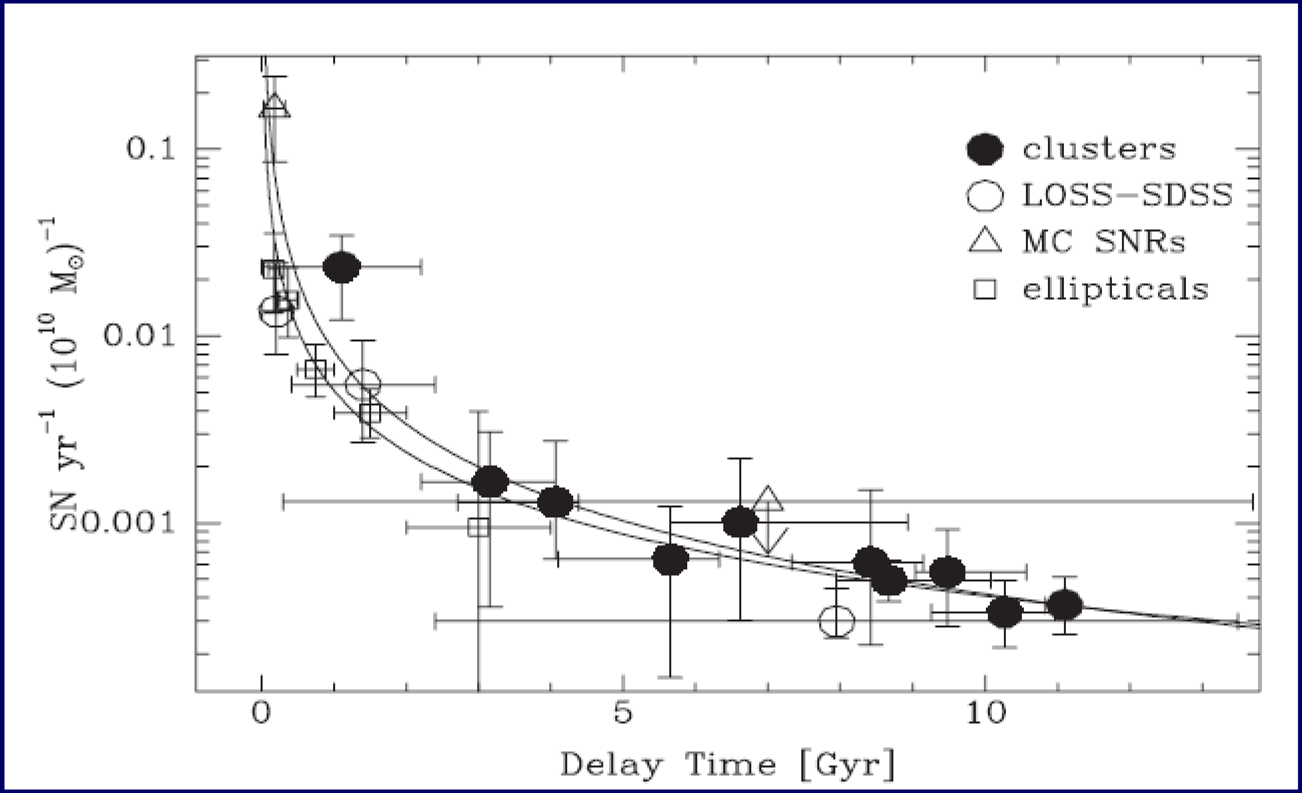
c. SN remnants vs. SFHs of individual cells of a single galaxy.

Emerging Picture:

* Wide distribution of delay times, looks like ~ t^{-1} .

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

- Shape like DD model, but 5-10X more SNe Ia than in binary population synthesis.



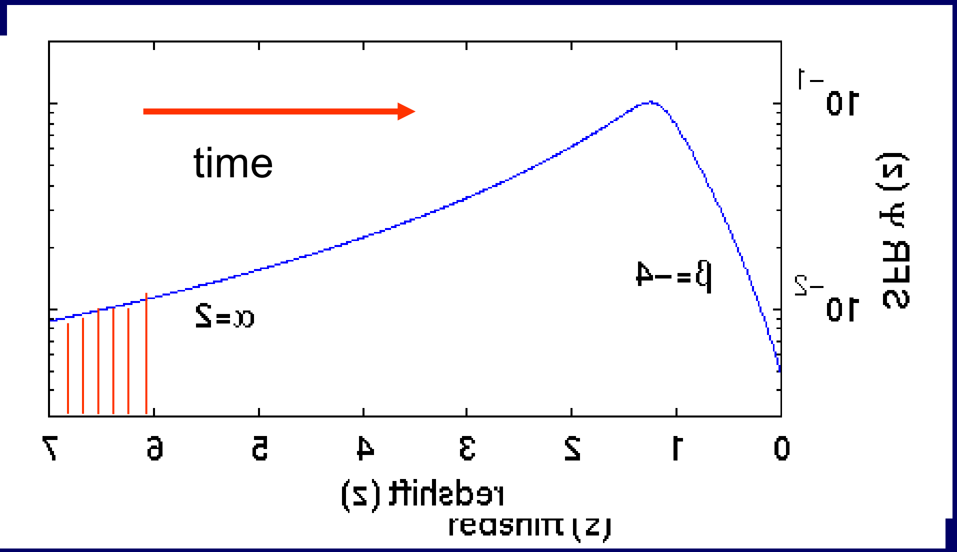
Future:

1. Deep SN remnant surveys in additional nearby galaxies (M31).

2. SN rates out to z>2 with HST WFC3

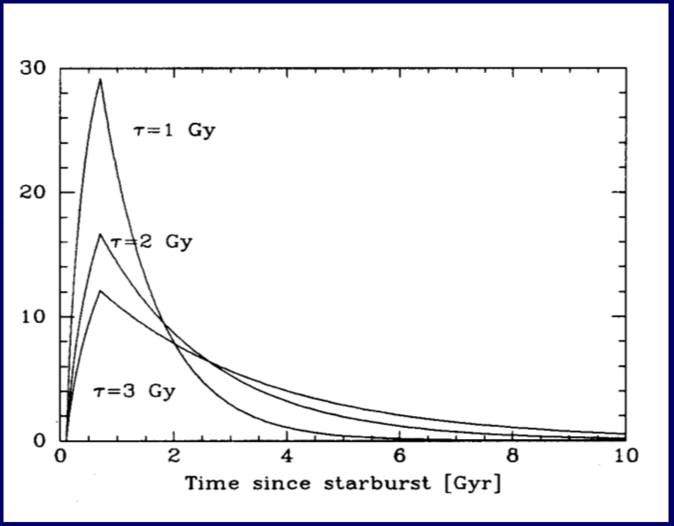
3. Better SFHs for galaxies monitored in already existing SN surveys

Star-formation history (z)

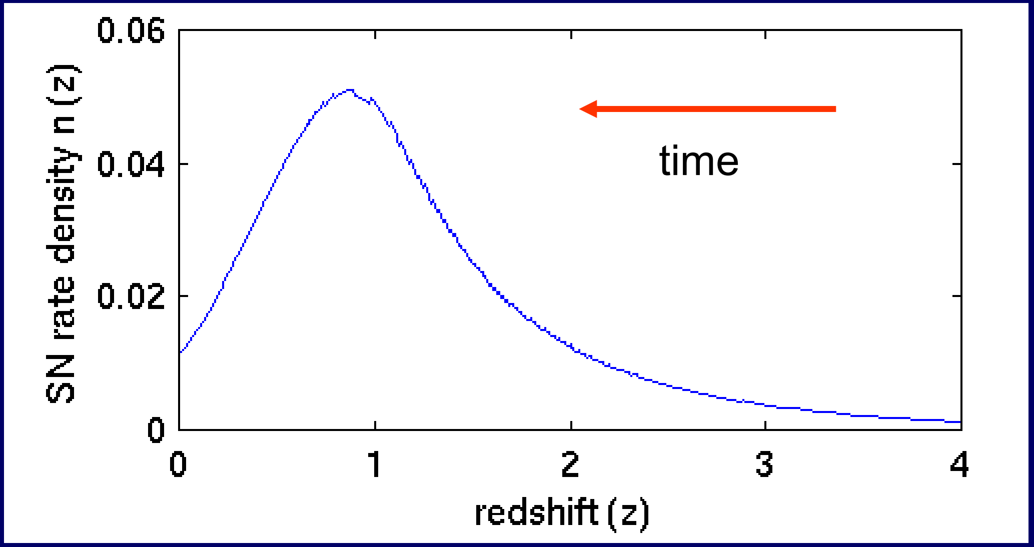


*

SN delay time distribution (t)



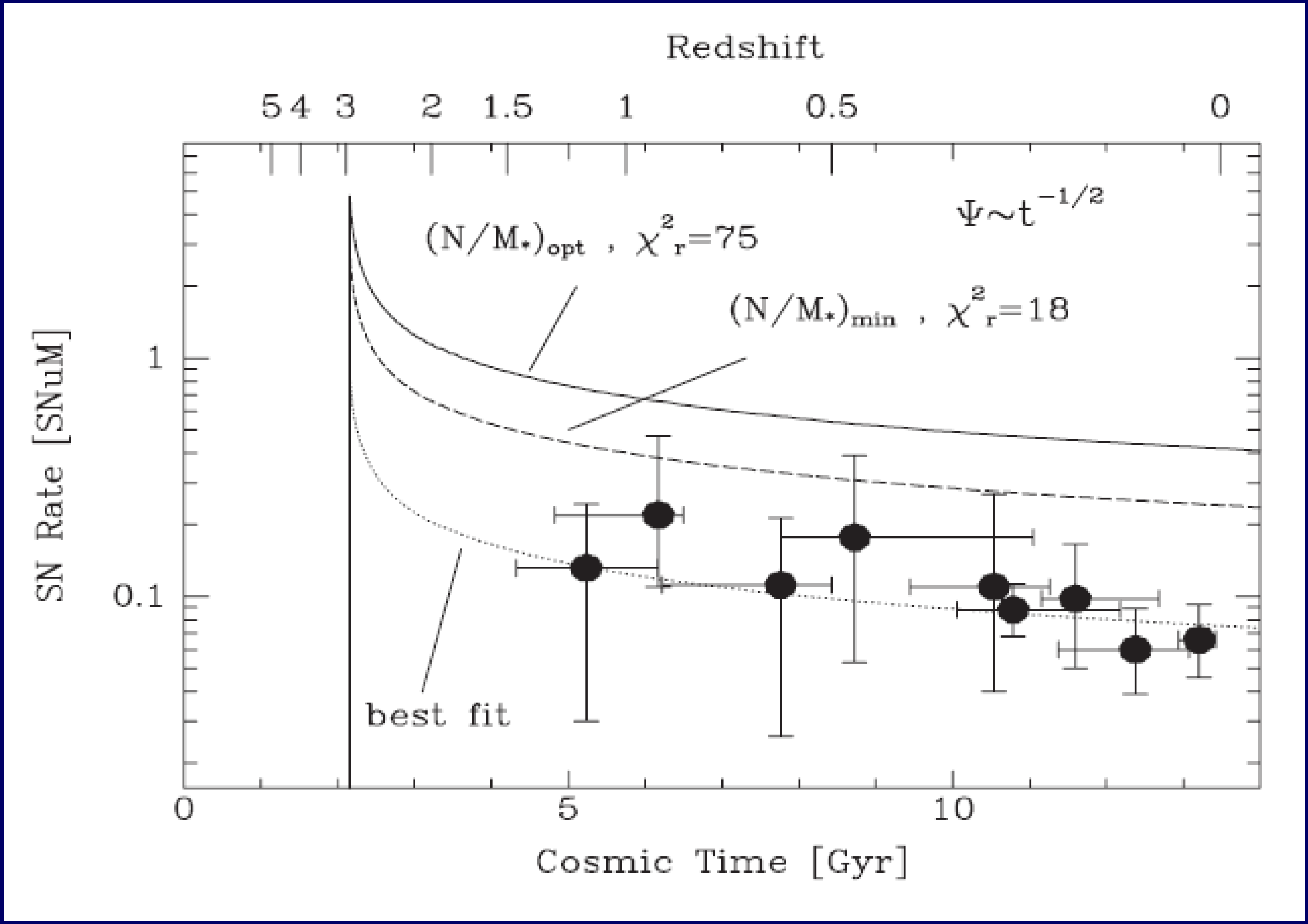
=

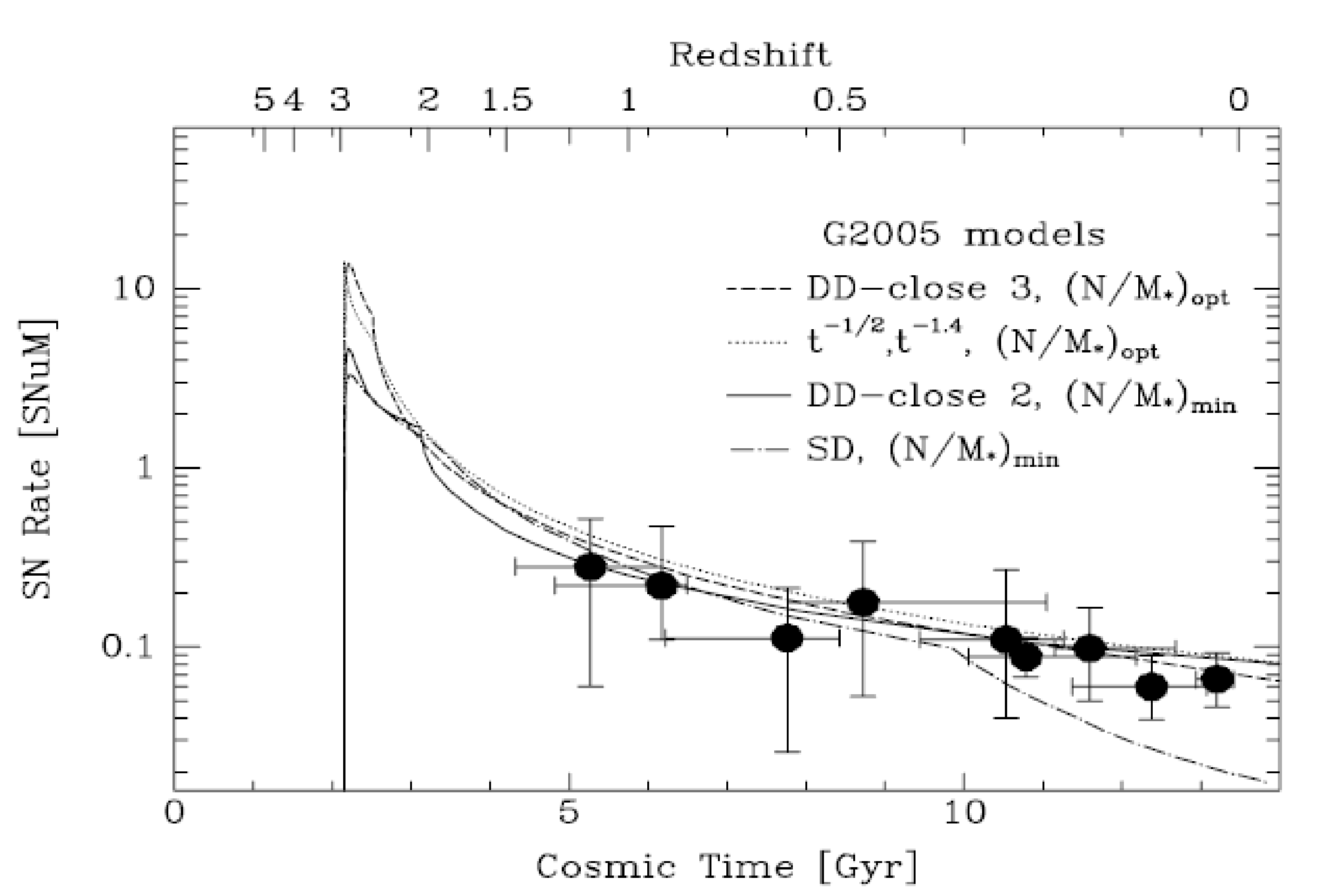


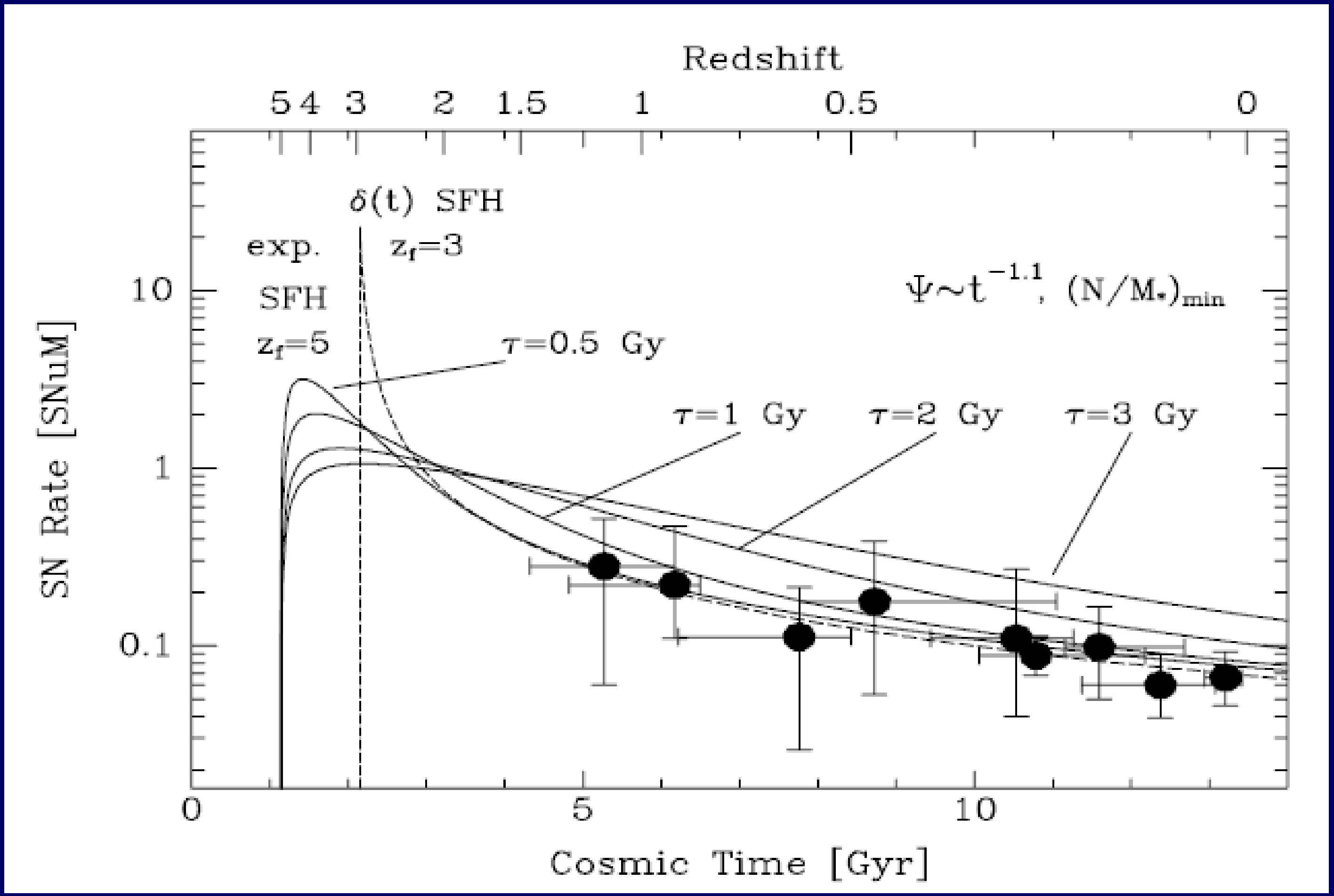
SN rate (z)

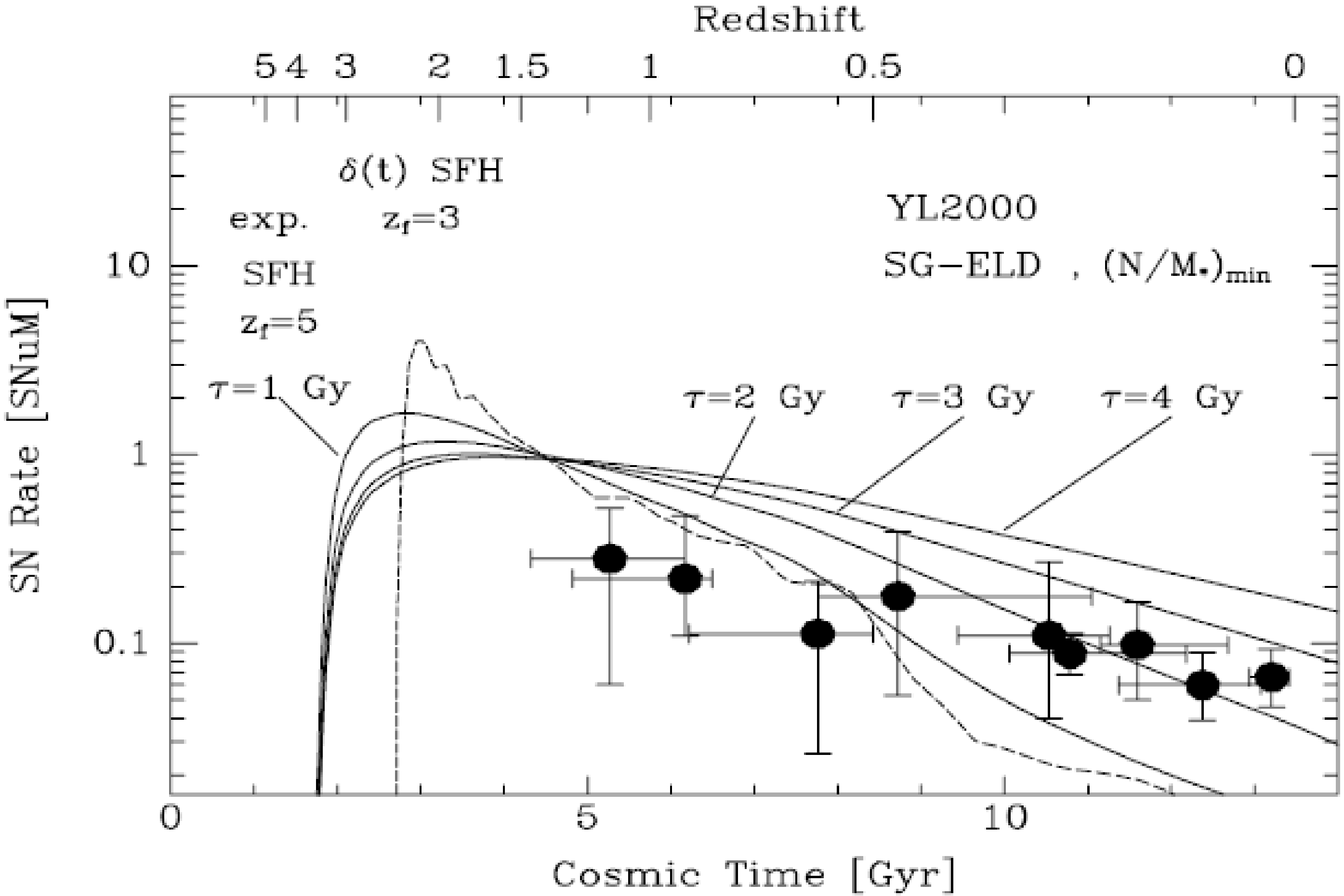
SN rate SFH delay function

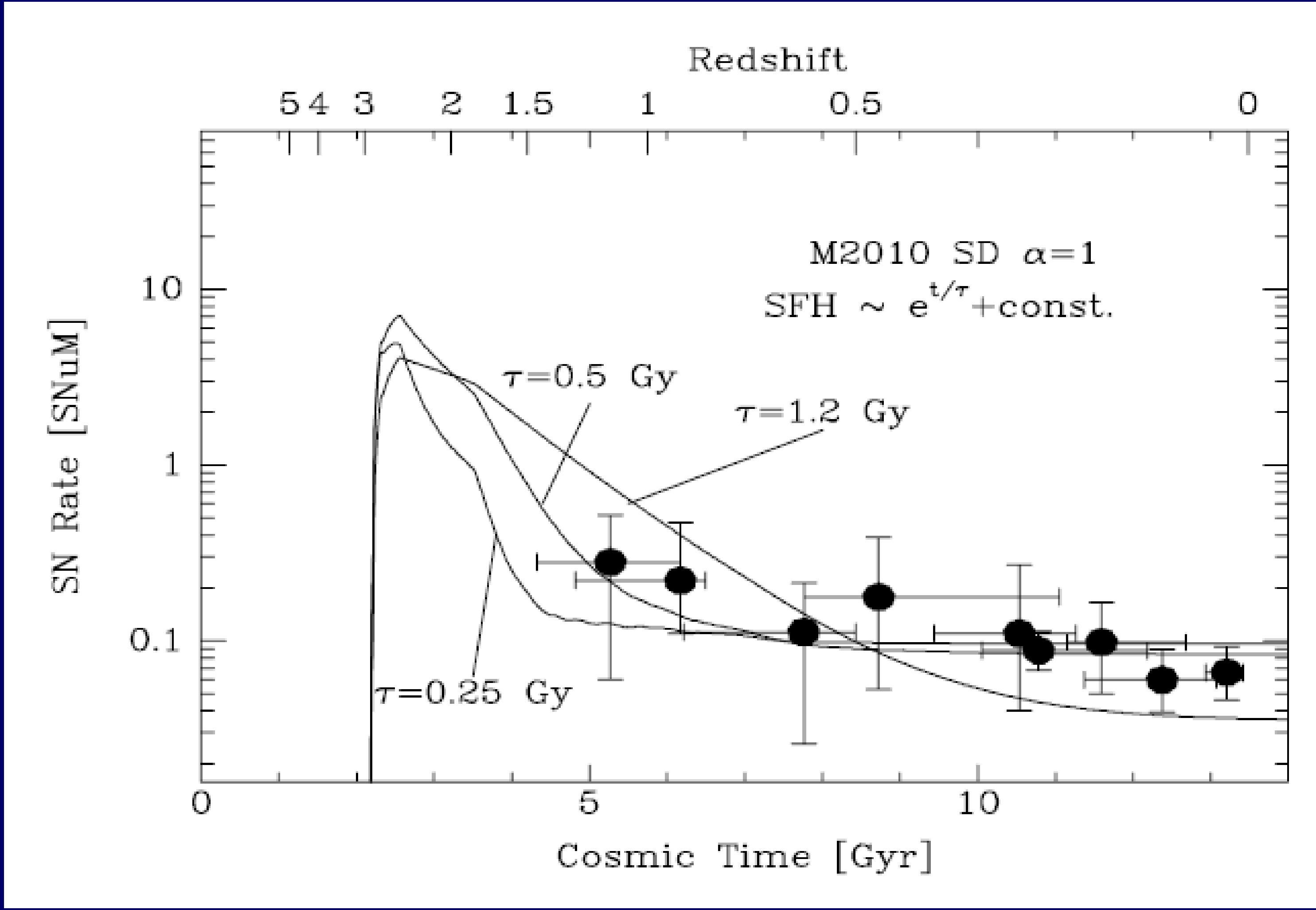
$$r(t) = \int_0^{t_0} S(t-\tau)\Psi(\tau)d\tau,$$


Redshift
5 4 3 2 1.5 1 0.5 0
$\Psi \sim t^{-1/2}$
$(N/M_*)_{opt}$, $\chi^2_r=75$
$(N/M_*)_{min}$, $\chi^2_r=18$
best fit
SN Rate [SNuM]
1
0.1
0 5 10
Cosmic Time [Gyr]


Redshift
5 4 3 2 1.5 1 0.5 0
G2005 models
DD−close 3, $(N/M_*)_{opt}$
$t^{-1/2}, t^{-1.4}$, $(N/M_*)_{opt}$
DD−close 2, $(N/M_*)_{min}$
SD, $(N/M_*)_{min}$
SN Rate [SNuM]
10
1
0.1
0 5 10
Cosmic Time [Gyr]


Redshift
5 4 3 2 1.5 1 0.5 0
δ(t) SFH
z_f=3
exp.
SFH
z_f=5
Ψ~t^-1.1, (N/M*)_min
τ=0.5 Gy
τ=1 Gy
τ=2 Gy
τ=3 Gy
10
1
0.1
SN Rate [SNuM]
0 5 10
Cosmic Time [Gyr]

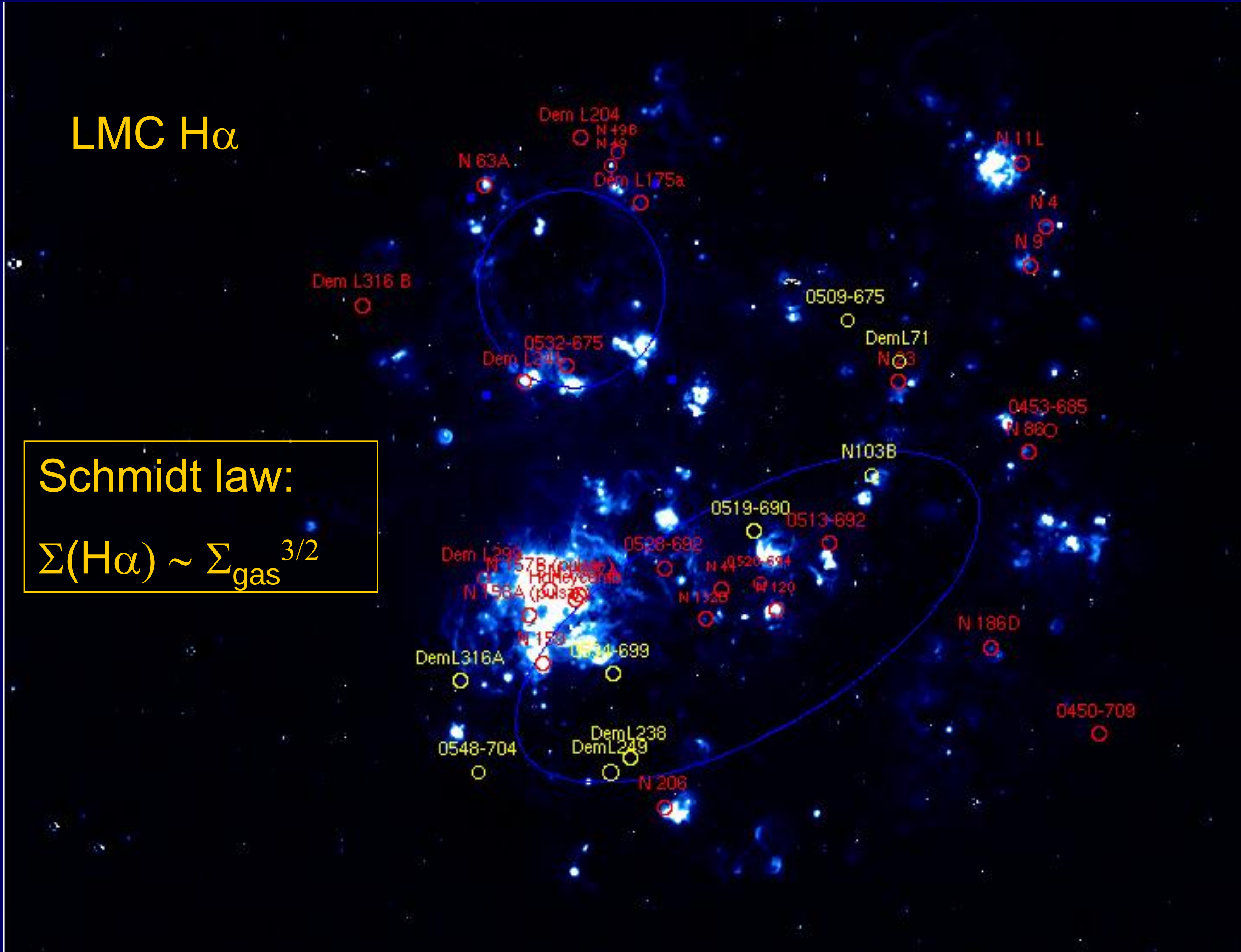

Redshift
5 4 3 2 1.5 1 0.5 0
δ(t) SFH
z_f=3
exp.
SFH
z_f=5
YL2000
SG−ELD , (N/M*)min
τ=1 Gy
τ=2 Gy
τ=3 Gy
τ=4 Gy
SN Rate [SNuM]
10
1
0.1
0 5 10
Cosmic Time [Gyr]

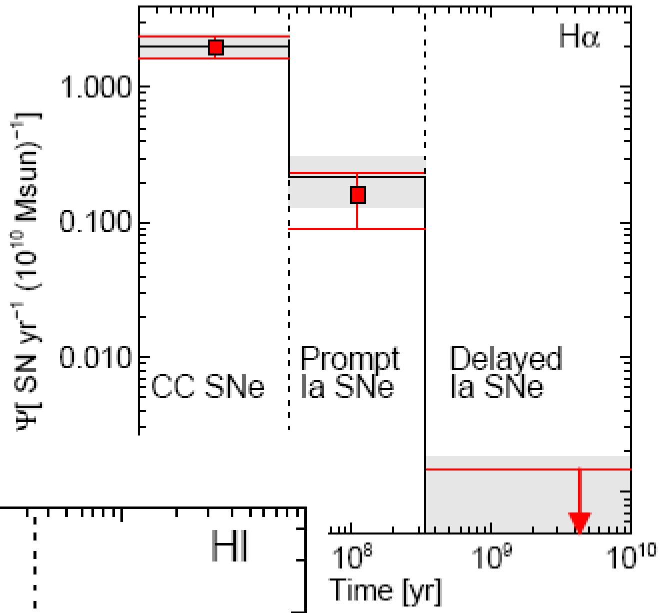

Redshift
5 4 3 2 1.5 1 0.5 0
M2010 SD α=1
SFH ~ $e^{t/\tau}$+const.
τ=0.5 Gy
τ=1.2 Gy
τ=0.25 Gy
SN Rate [SNuM]
10
1
0.1
0 5 10
Cosmic Time [Gyr]

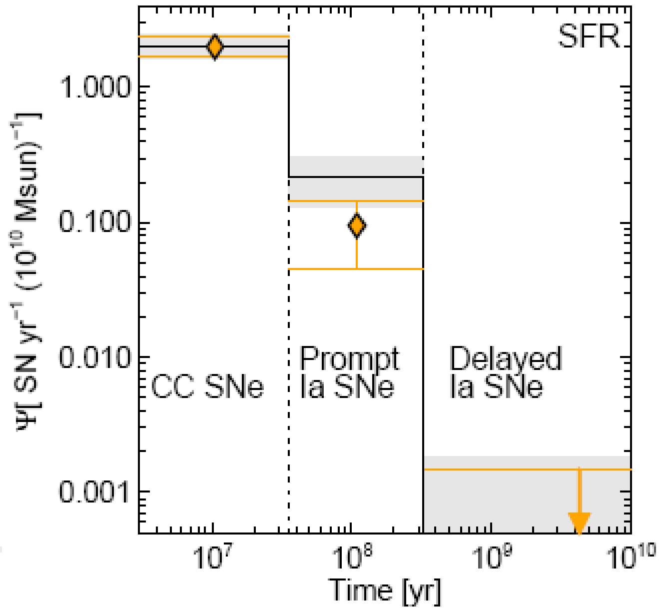
LMC Hα

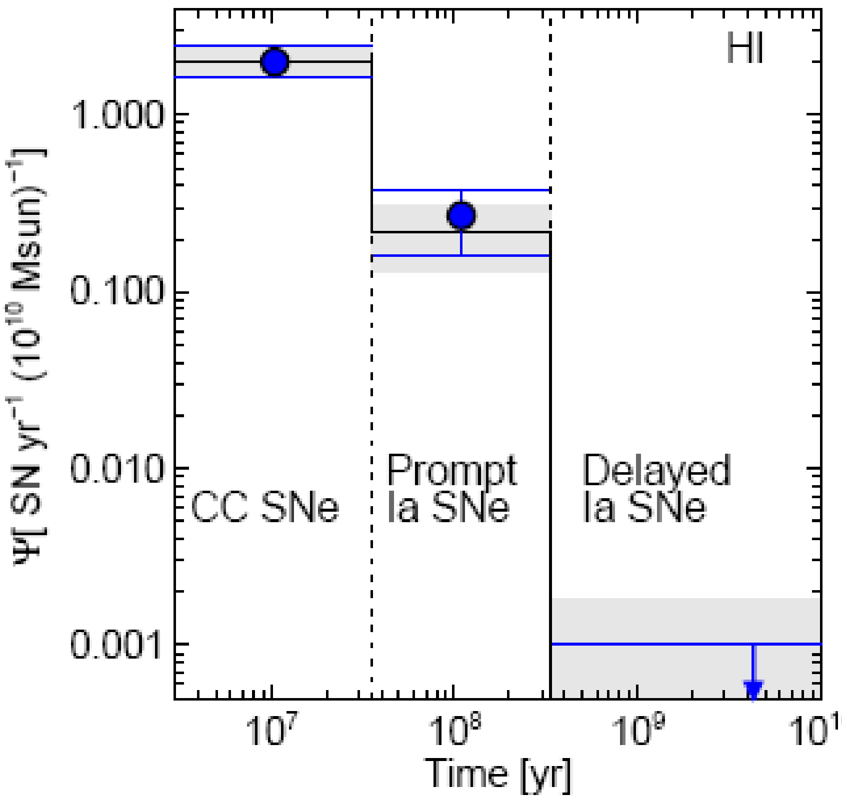
Schmidt law:

$$\Sigma(H\alpha) \sim \Sigma_{gas}^{3/2}$$









LMC+SMC delay function from SNRs + SFH from resolved stellar populations.

Current SN rate:

2-5 SNe/millenium

1.5-3.5 SNe/century/10^{10} M_{sun}

How long, in principle, can we see a SNR?

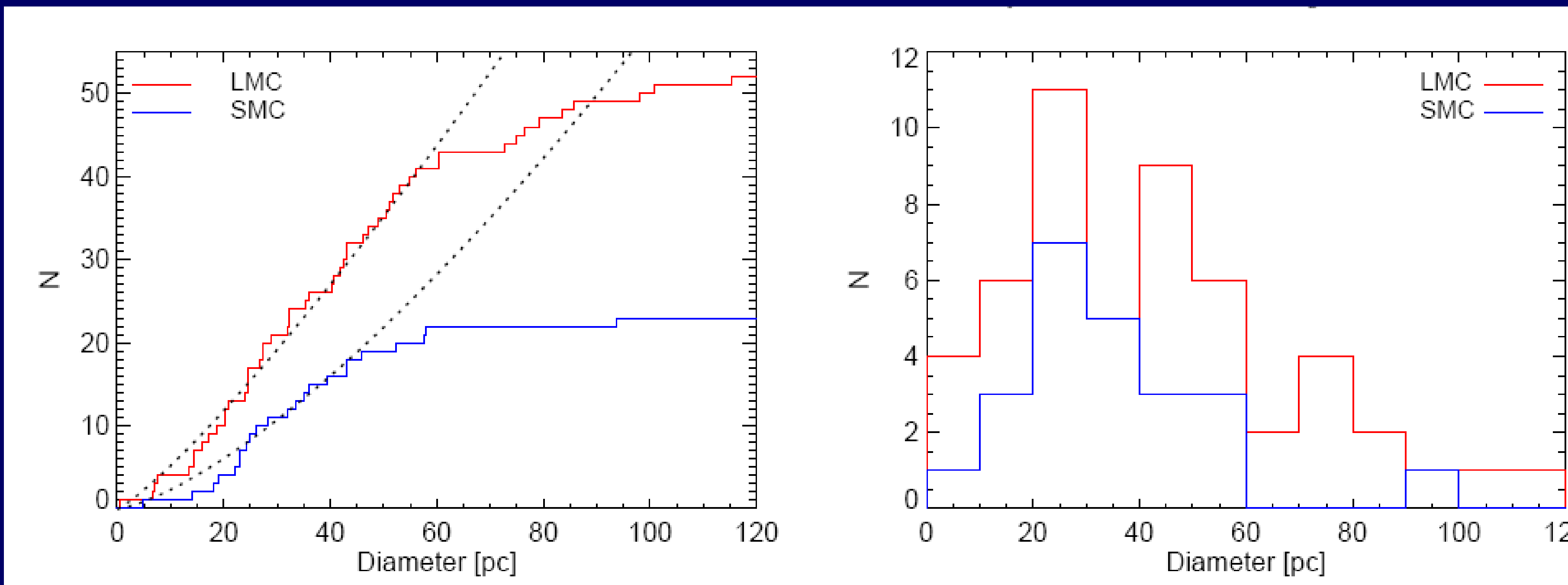
Badenes, Maoz & Draine (2010):

Visibility time of SNRs in Magellanic Clouds

= lifetime of Sedov-Taylor phase

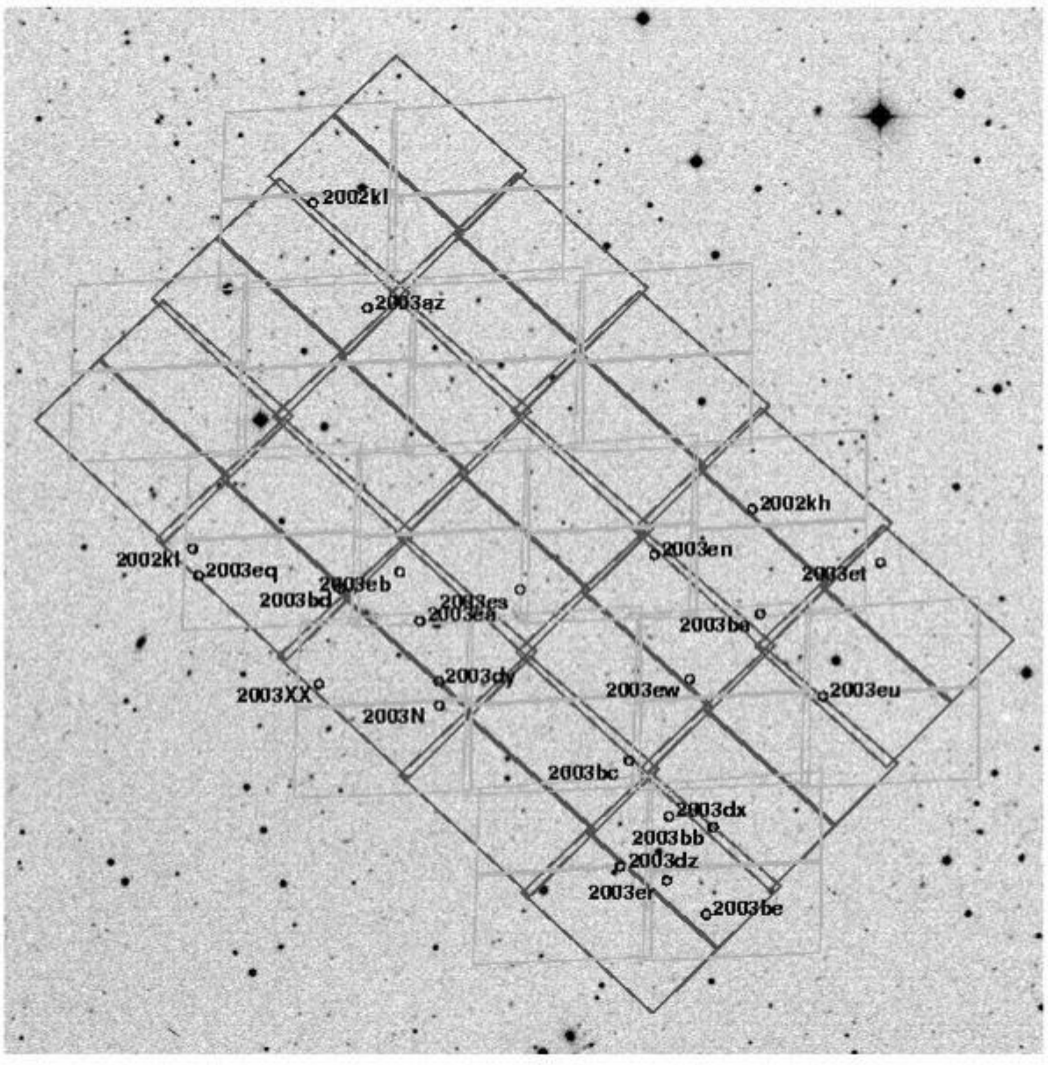
$\sim E_o^{1/4} \ \rho^{-1/2}$

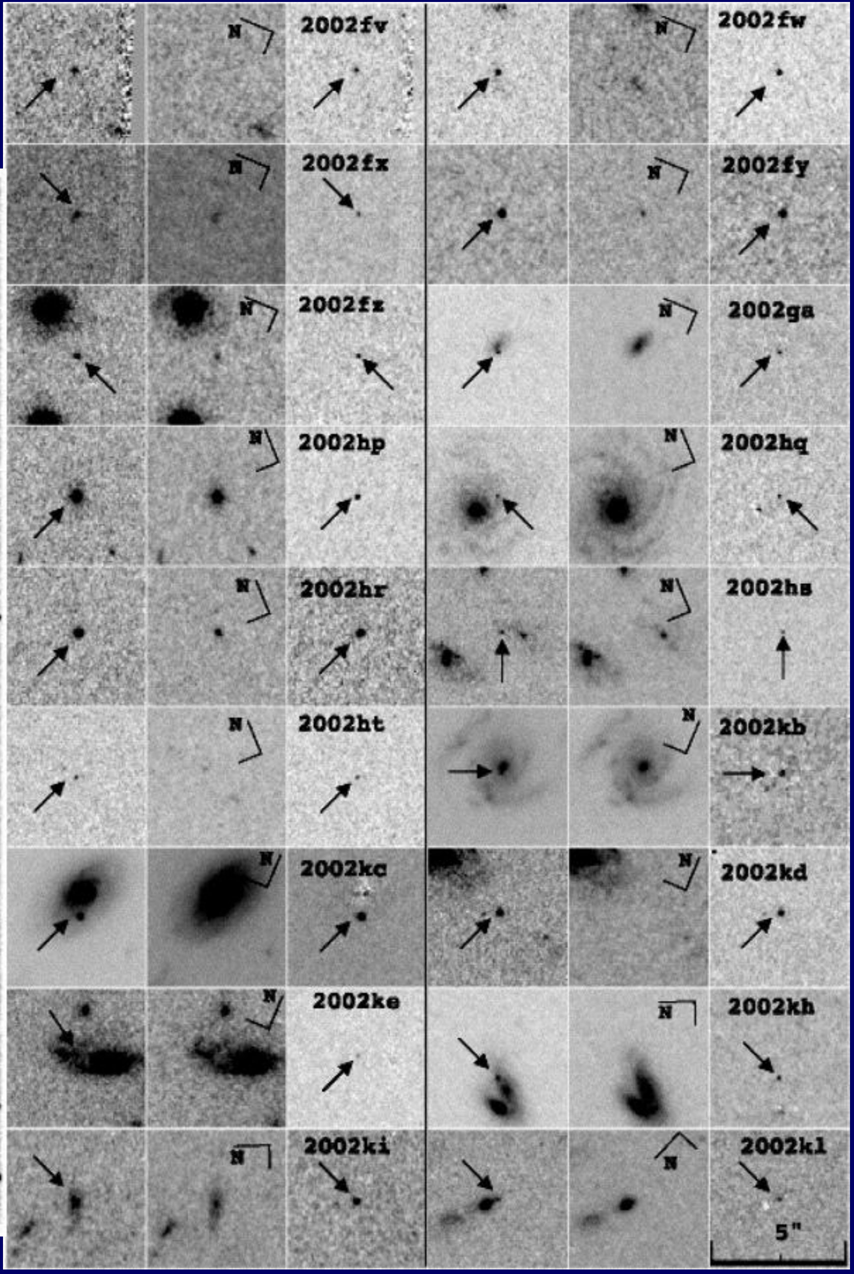
ambient density

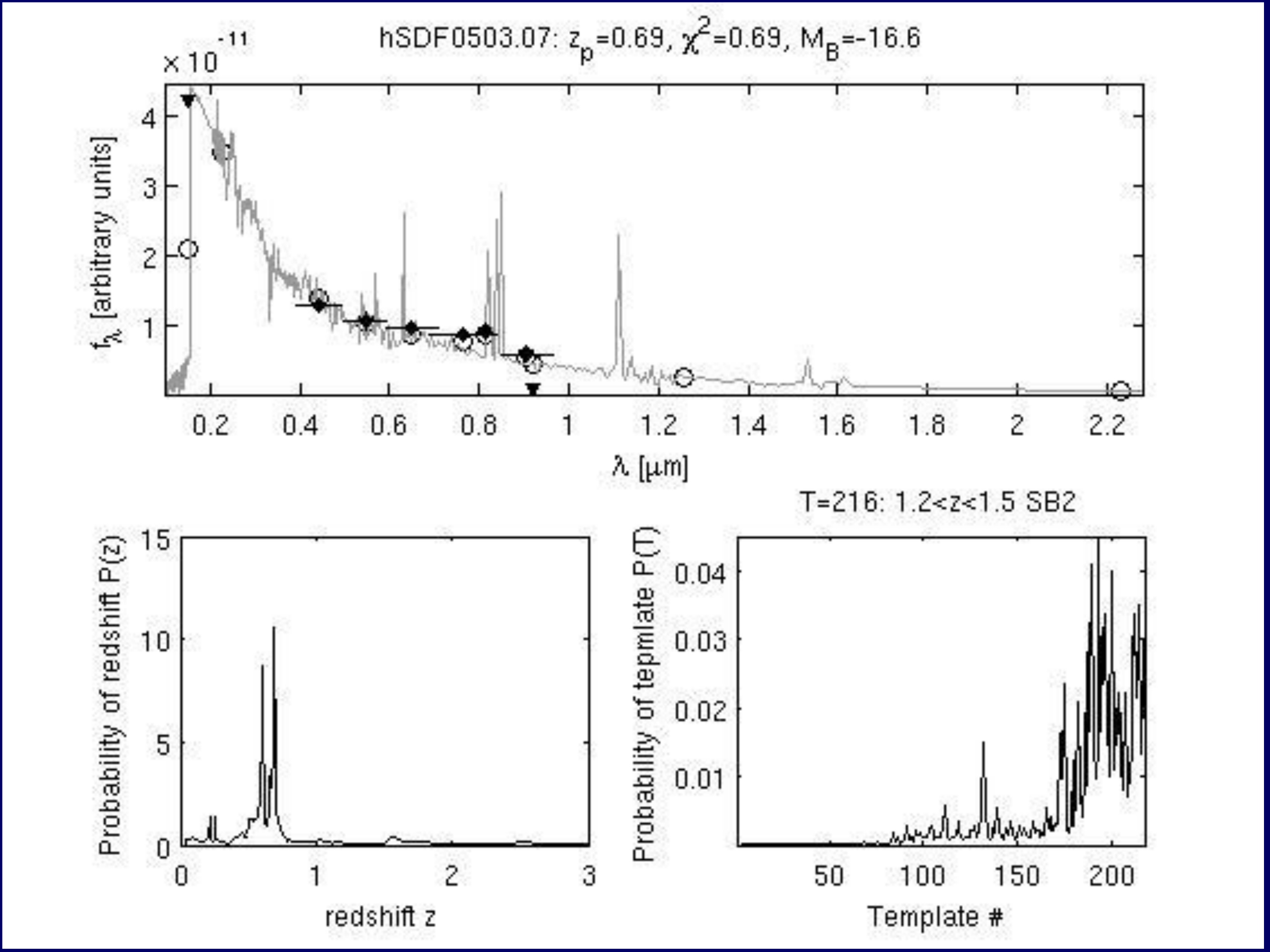


LMC
SMC
N
Diameter [pc]
0
10
20
30
40
50
60
80
100
120
LMC
SMC
N
Diameter [pc]
0
2
4
6
8
10
12

HST/ACS GOODS (~700 orbits) Riess, Dahlen, Strolger et al. 2004-2008,
~80 SNe, 46 SNe-Ia, 24 @ z>1



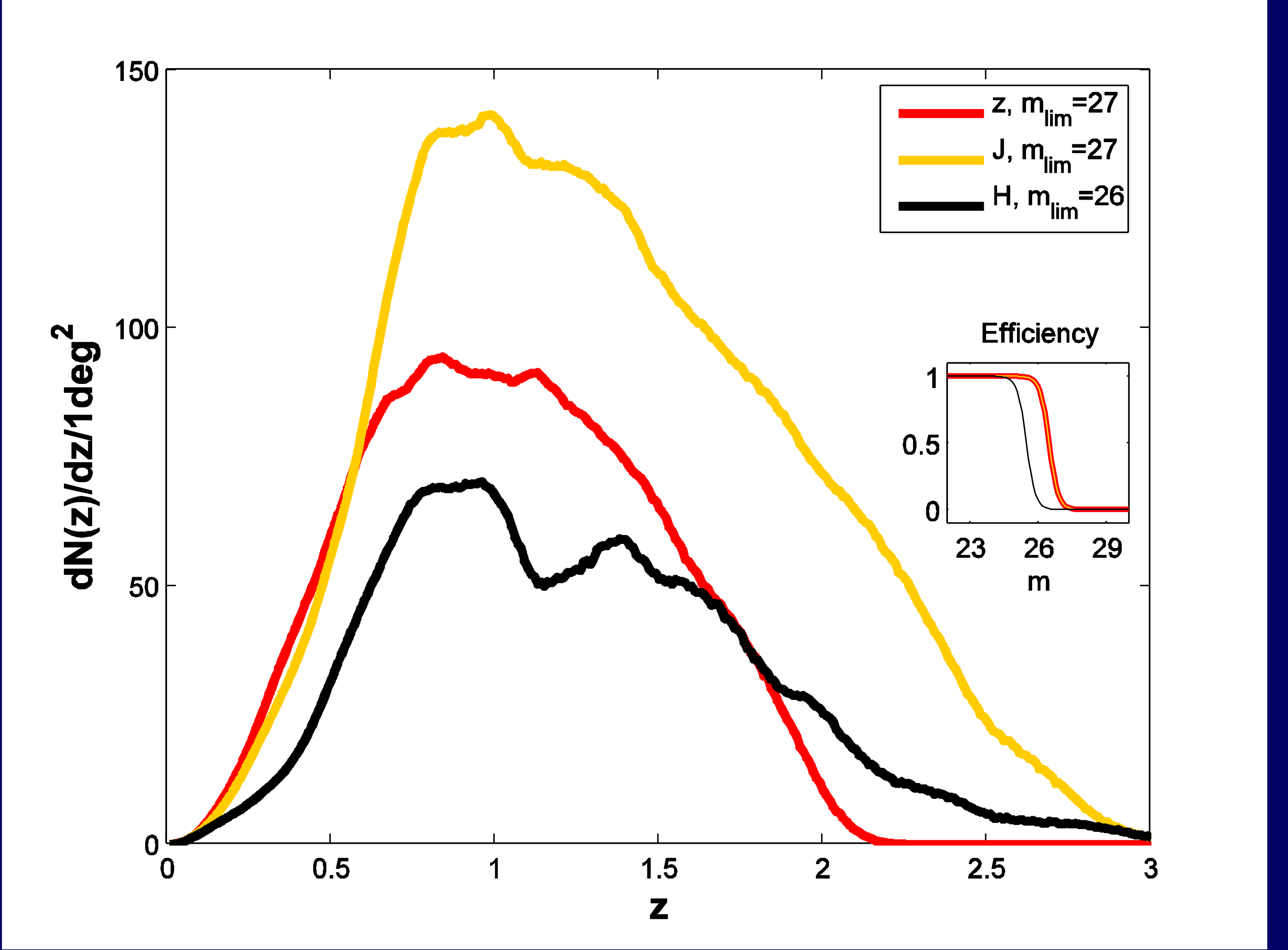


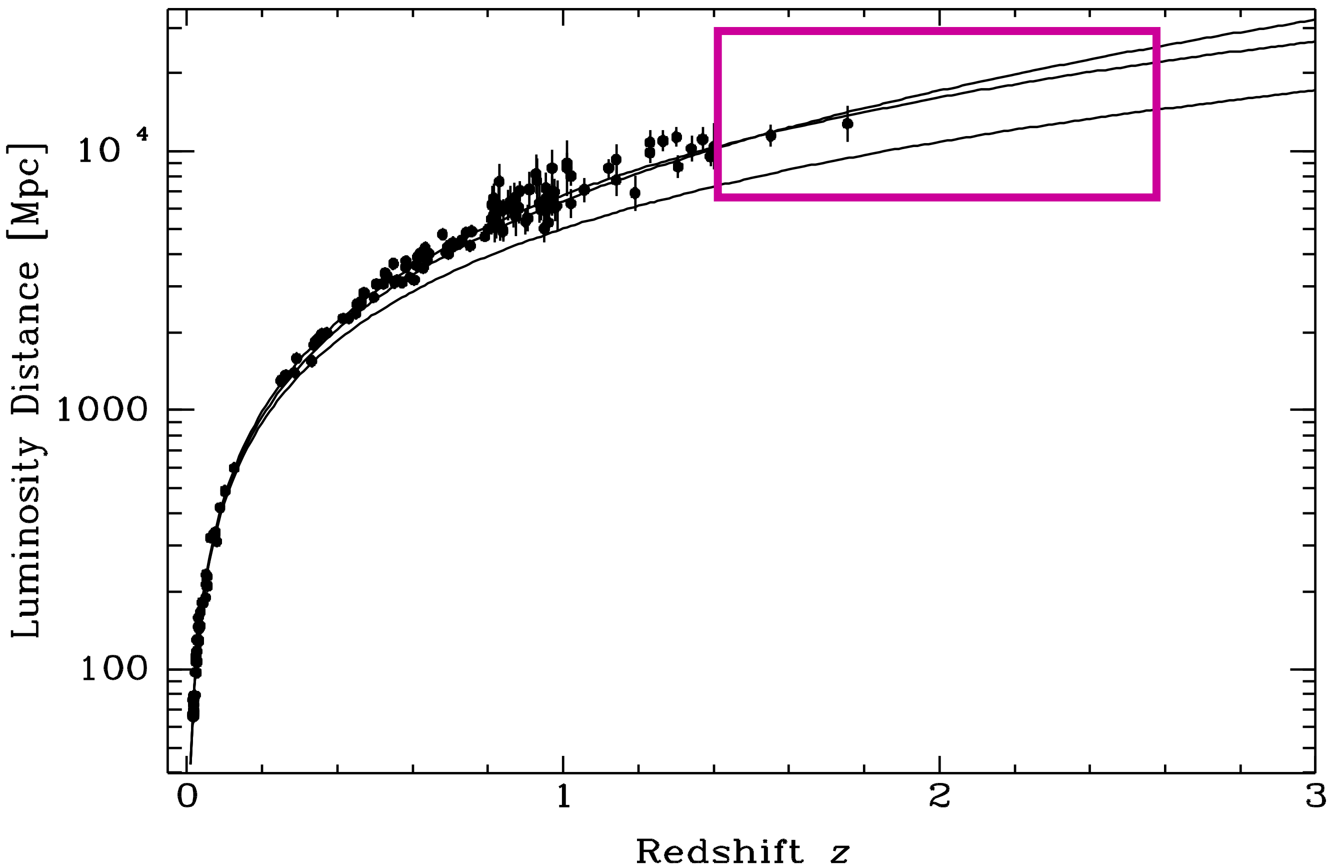

hSDF0503.07: z_p=0.69, χ^2=0.69, M_B=-16.6
× 10^-11
f_λ [arbitrary units]
λ [μm]
T=216: 1.2<z<1.5 SB2
Probability of redshift P(z)
redshift z
Probability of tepmlate P(T)
Template #

With the new HST-WFC3--Potential for SNe out to z~2.5:

Two approved HST MC Treasury programs

(1400 orbits)   predictions by K. Sharon

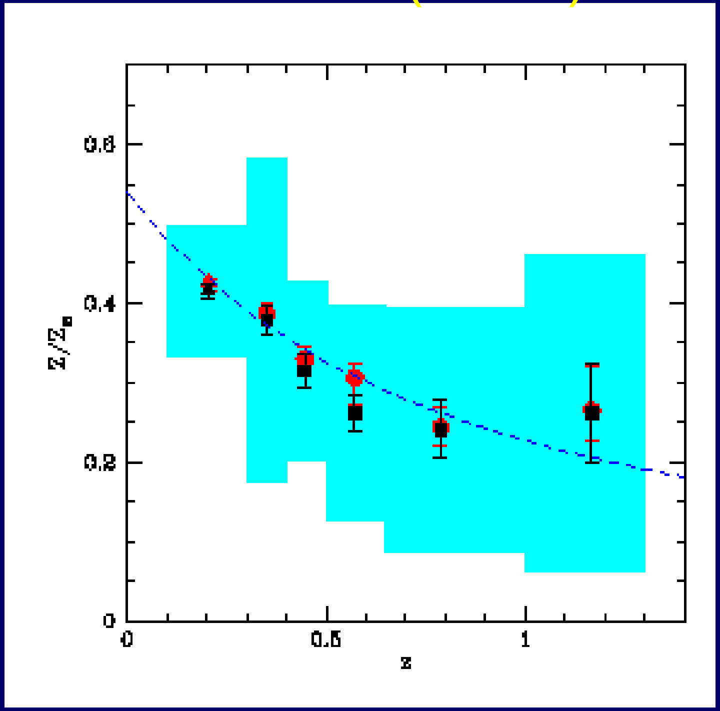




Luminosity Distance [Mpc]
10^4
1000
100
0
1
2
3
Redshift z

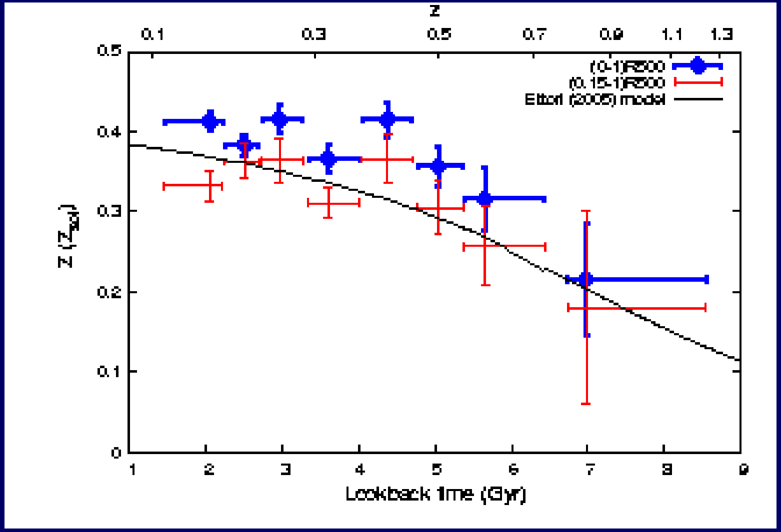
Iron in clusters (ICM+stars) easy to detect and to deduce total iron mass.

Balestra et al. (2007)



Maughan et al. (2008)

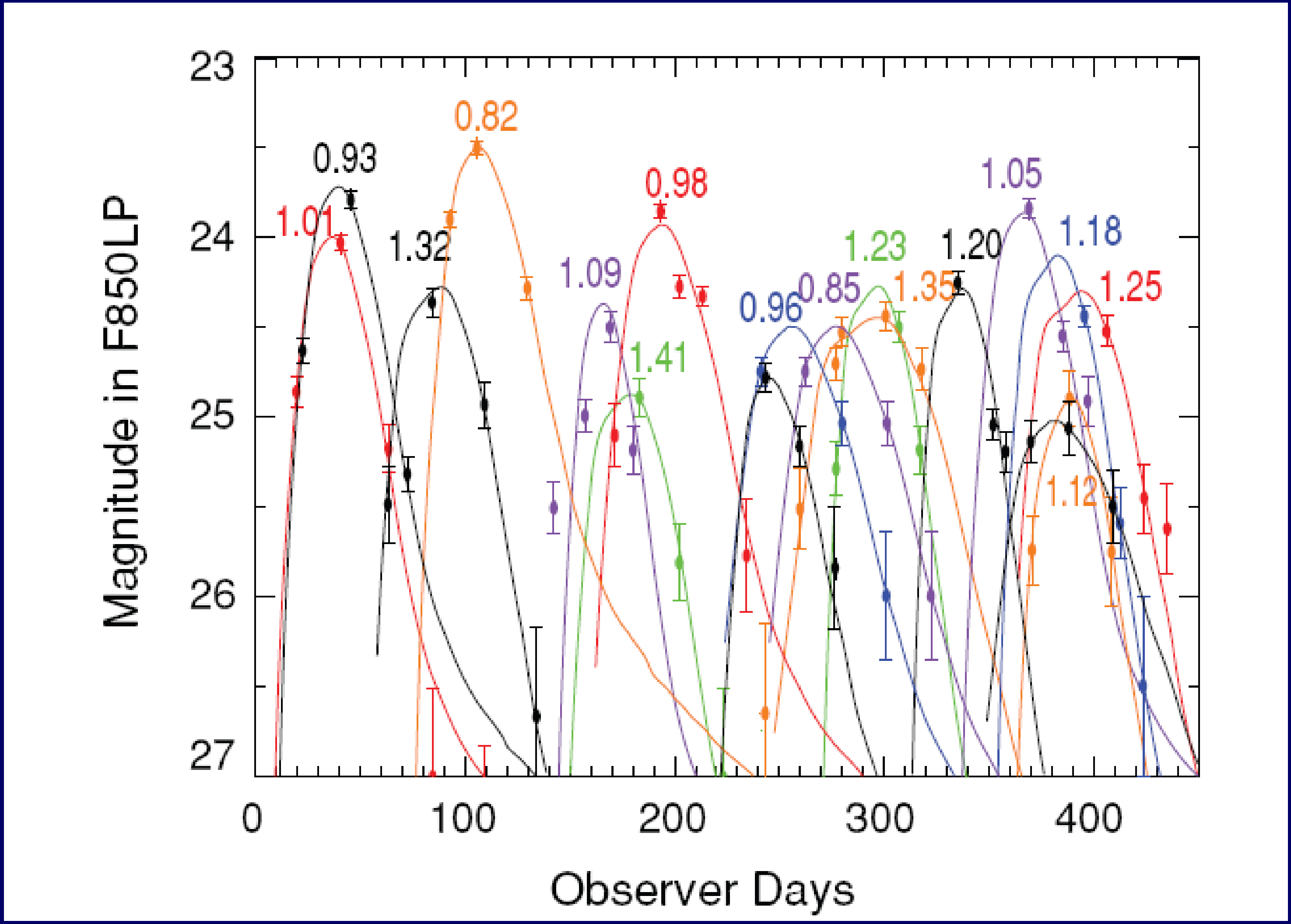
(but see Ehlert & Ulmer 2009)



Iron yields of individual SNe known directly from observations (e.g., Mazzali et al. 2007):

SN-Ia: M(Fe)=0.7 Msun

Dawson+2009, survey for SNe in clusters at 0.9<z<1.4



SN rate SFH delay function

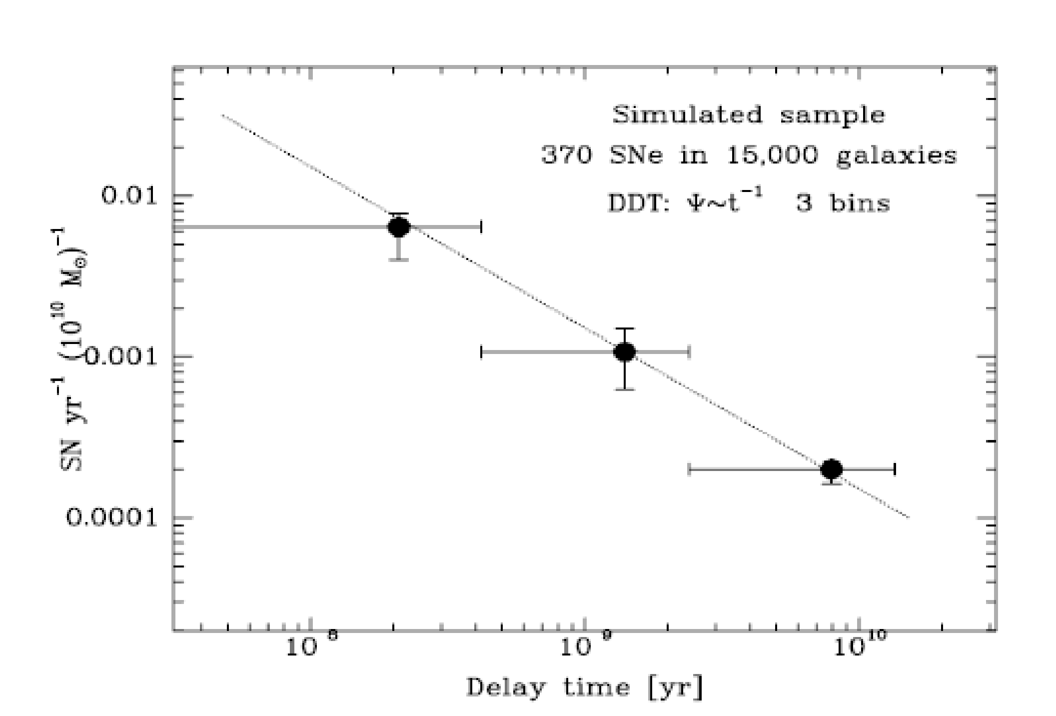
$$r(t) = \int_0^{t_0} S(t-\tau)\Psi(\tau)d\tau,$$

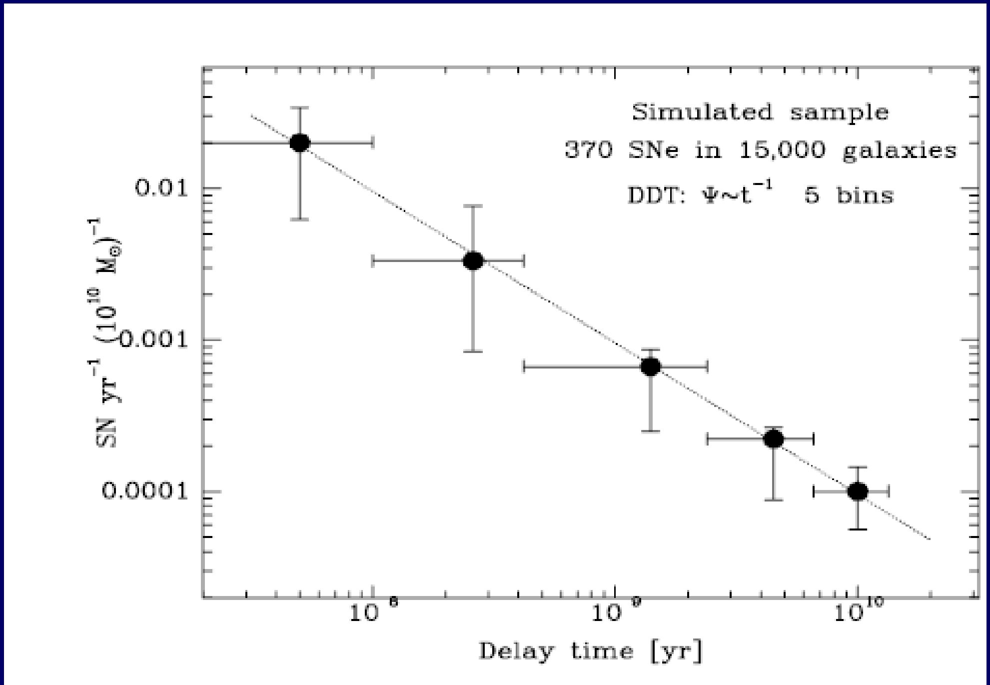
$$r_i = \sum_{j=1}^{K} m_{ij}\Psi_j,$$

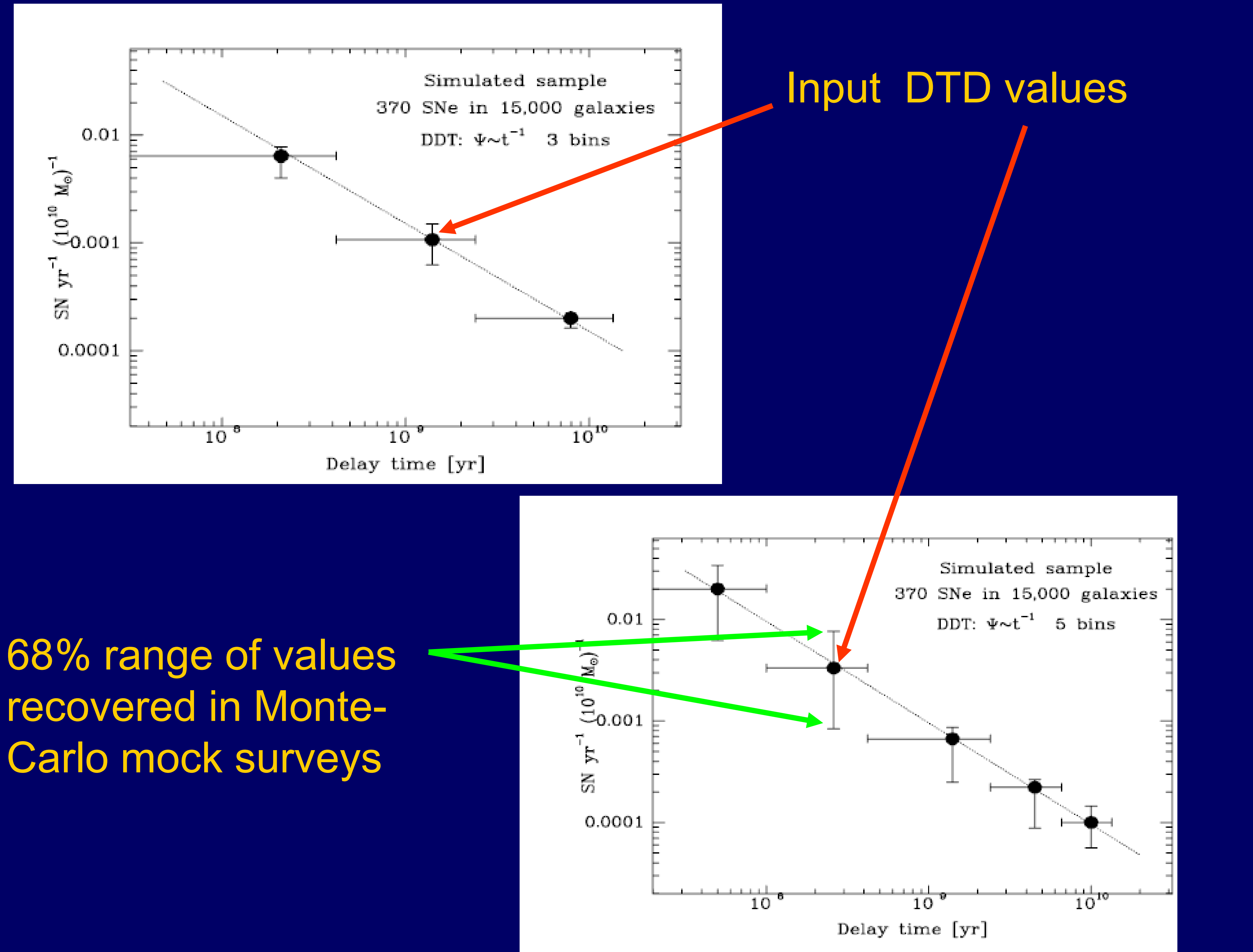
expect. value visibility time

$$\lambda_i = r_i t_i,$$

$$P(n_i|\lambda_i) = (e^{-\lambda_i}\lambda_i^{n_i})/n_i!$$


Simulated sample
370 SNe in 15,000 galaxies
DDT: Ψ~t^-1 3 bins
0.01
0.001
0.0001
SN yr^-1 (10^10 M⊙)^-1
10^8
10^9
10^10
Delay time [yr]

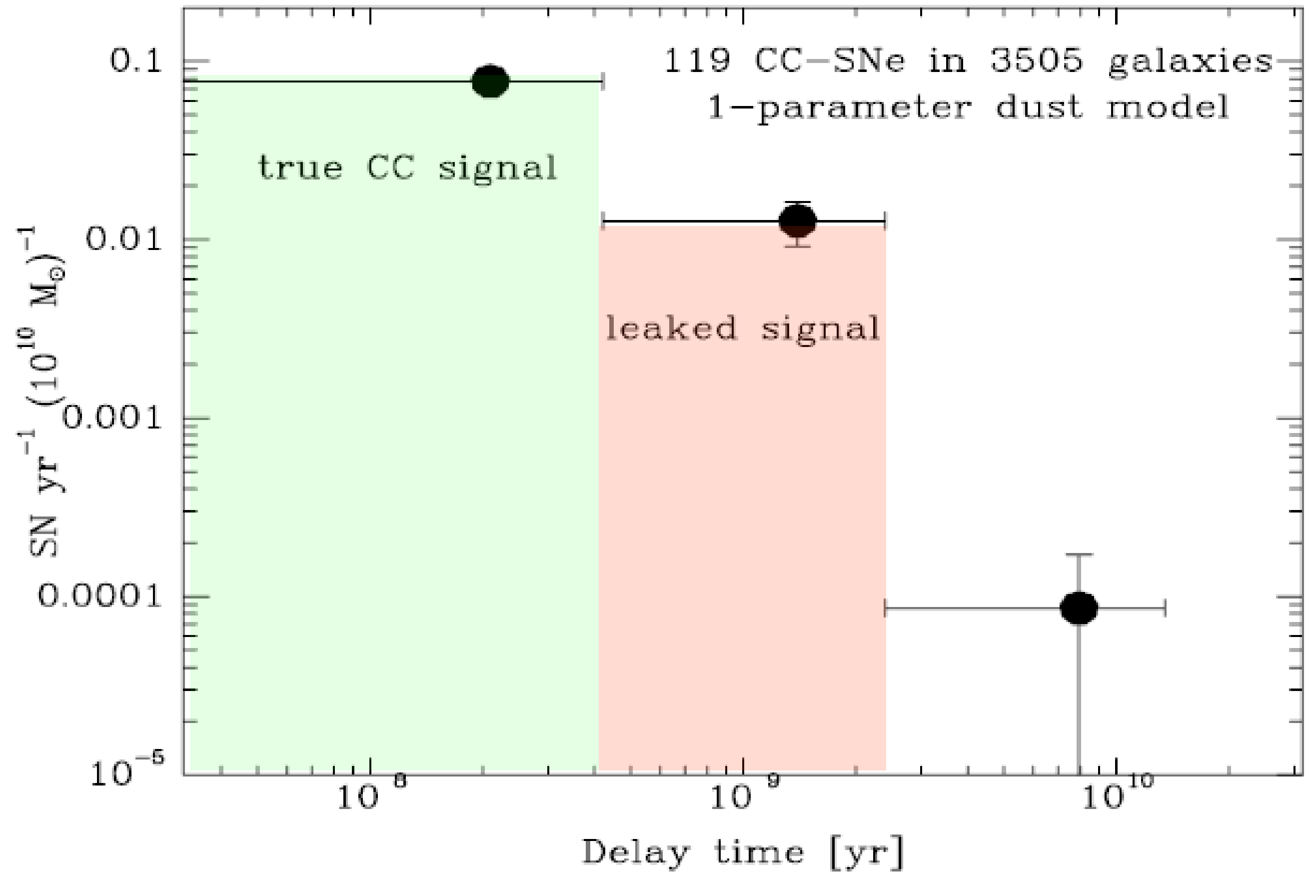

Simulated sample
370 SNe in 15,000 galaxies
DDT: Ψ~t^-1 5 bins
0.01
0.001
0.0001
SN yr^-1 (10^10 M⊙)^-1
10^8
10^9
10^10
Delay time [yr]

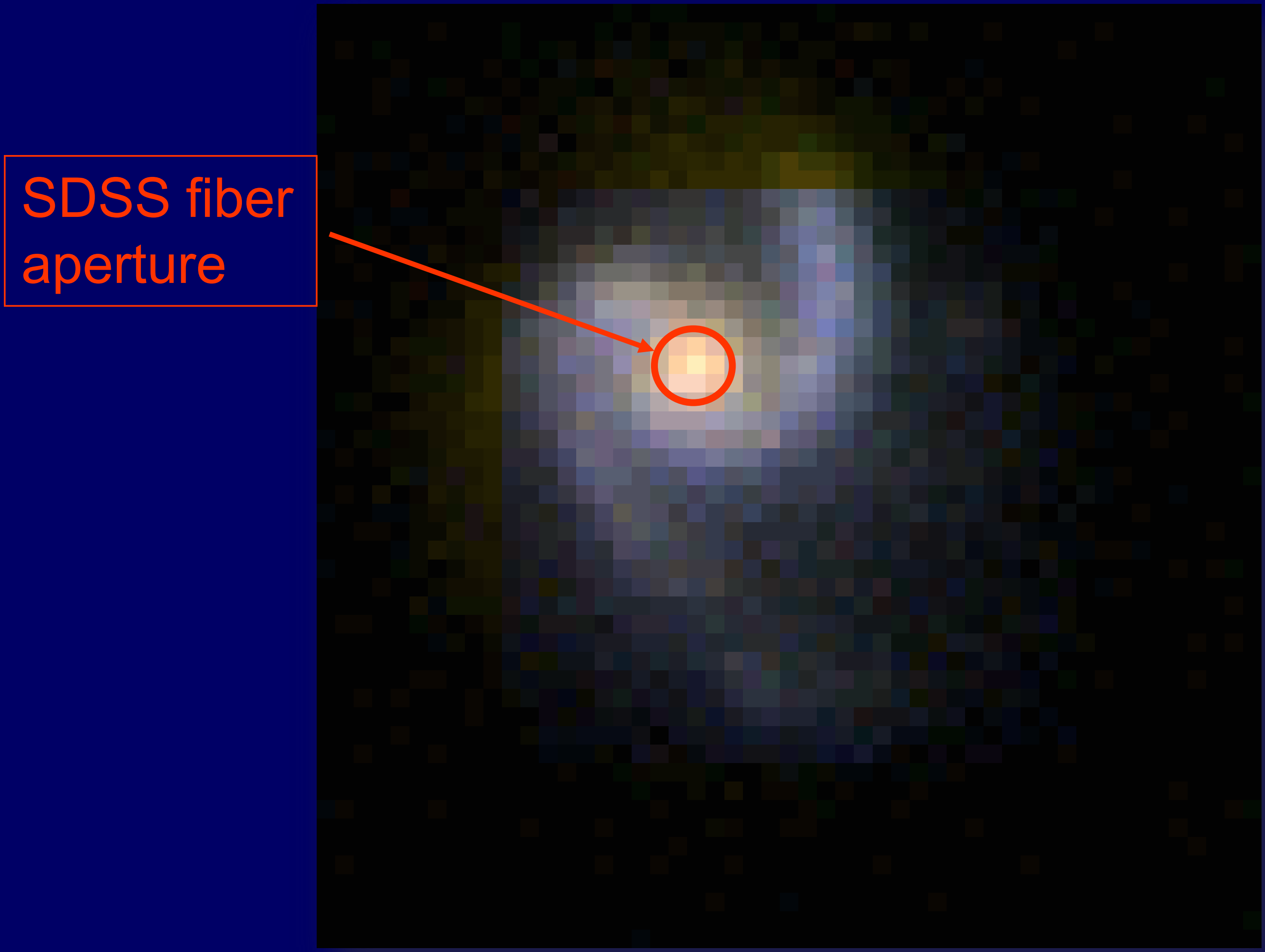

Simulated sample
370 SNe in 15,000 galaxies
DDT: Ψ~t^-1 3 bins
0.01
0.001
0.0001
SN yr^-1 (10^10 M⊙)^-1
10^8
10^9
10^10
Delay time [yr]
Input DTD values
Simulated sample
370 SNe in 15,000 galaxies
DDT: Ψ~t^-1 5 bins
0.01
0.001
0.0001
SN yr^-1 (10^10 M⊙)^-1
10^8
10^9
10^10
Delay time [yr]
68% range of values recovered in Monte-Carlo mock surveys

Subsample of LOSS:

3505 galaxies with SDSS spectra, star-formation history reconstructions by Tojeiro+2009

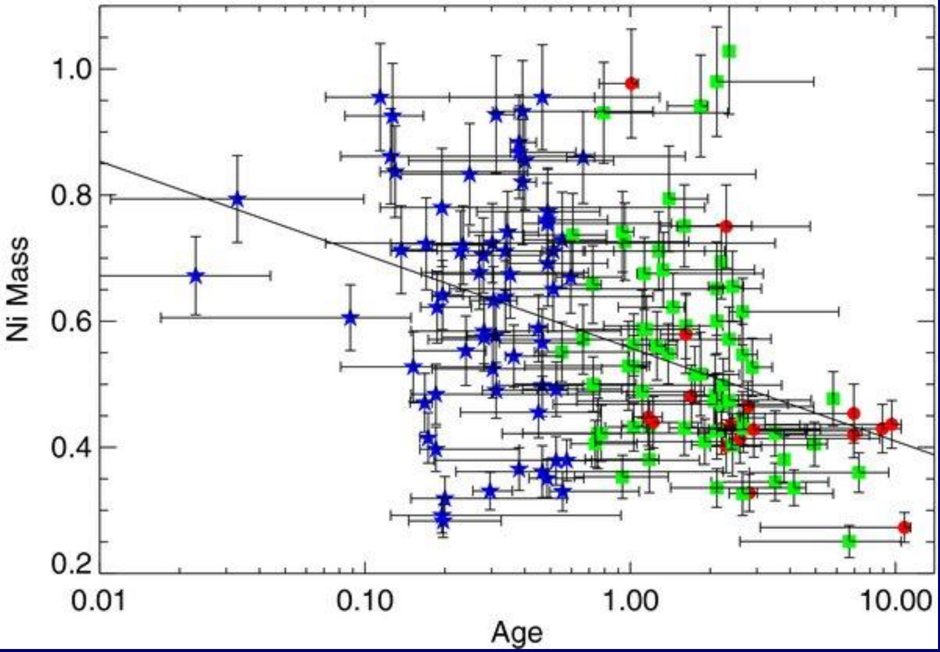
Core-collapse SNe



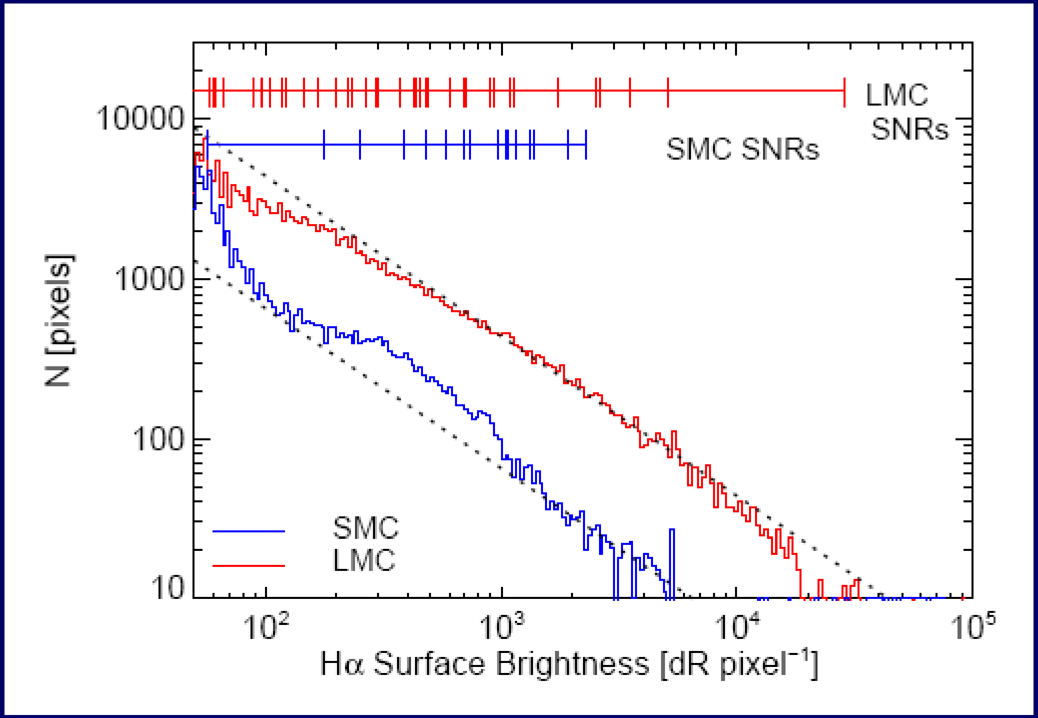

SDSS fiber aperture

…and different environments can make different Ia's

Howell et al. 2009



Young hosts old hosts


LMC
SNRs
SMC SNRs
10000
1000
100
10
N [pixels]
SMC
LMC
10^2
10^3
10^4
10^5
Hα Surface Brightness [dR pixel^{-1}]

Formation Efficiency of SNe-Ia

If “prompt” SNe-Ia explode within 400 Myr:

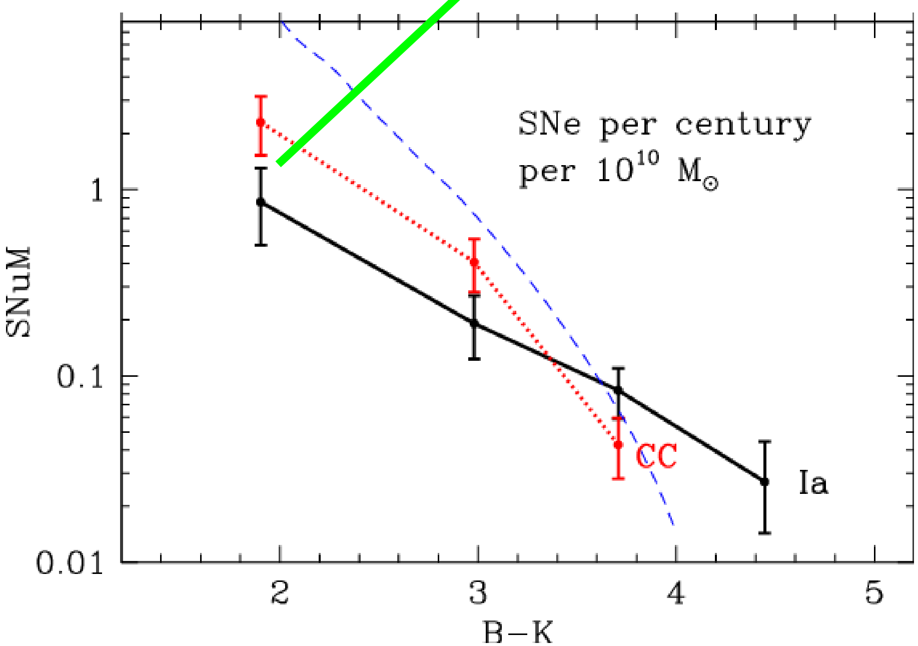
then

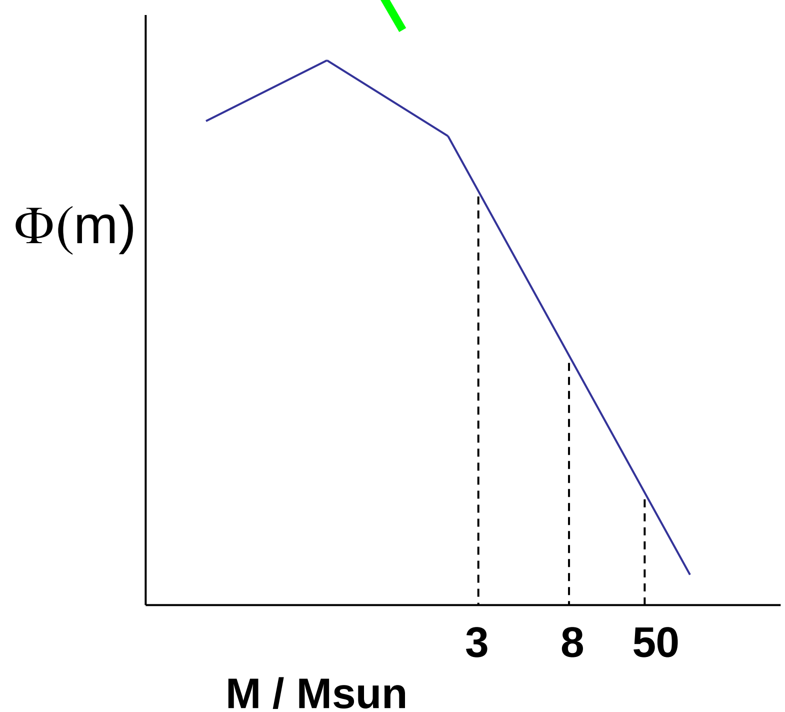
Primary star must be > 3 Msun

What fraction of all stars with m_{init}=3-8 M_{sun} go SN-Ia?

$$\frac{N_{\mathrm{Ia}}}{N_{\mathrm{CC}}} \quad . \quad \sim 1/9$$

~1/3 ~1/3





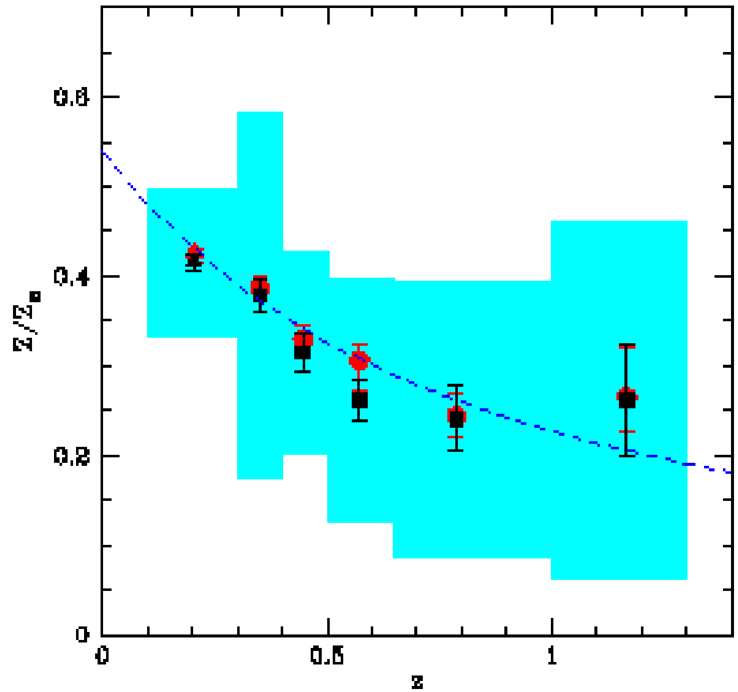
$$\eta_B = \frac{N_{\mathrm{Ia}}/t}{M_*/t}$$

~ 5-10%

~(1-2)x10^{-3} ~50

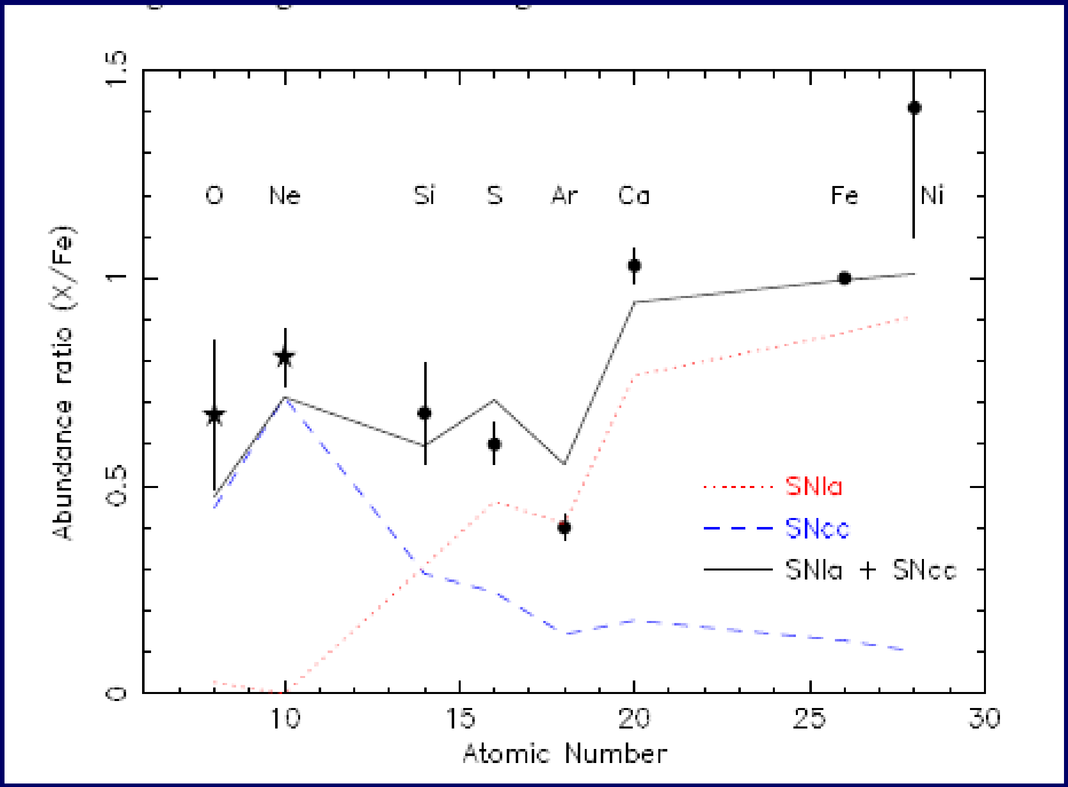
SN-Ia/Msun Msun

e.g. Dilday et al. 2008



$$\eta_{\mathrm{Fe}} = \frac{0.8 M_{\mathrm{Fe}}}{Y_{\mathrm{Fe}} M_*} \frac{\int_{0.1}^{100} m\phi(m)dm}{\int_{3}^{8} \phi(m)dm}$$ ~ 10-20%

De Plaa et al. 2007



ICM abundances: $N_{Ia}/N_{CC} \sim 1$

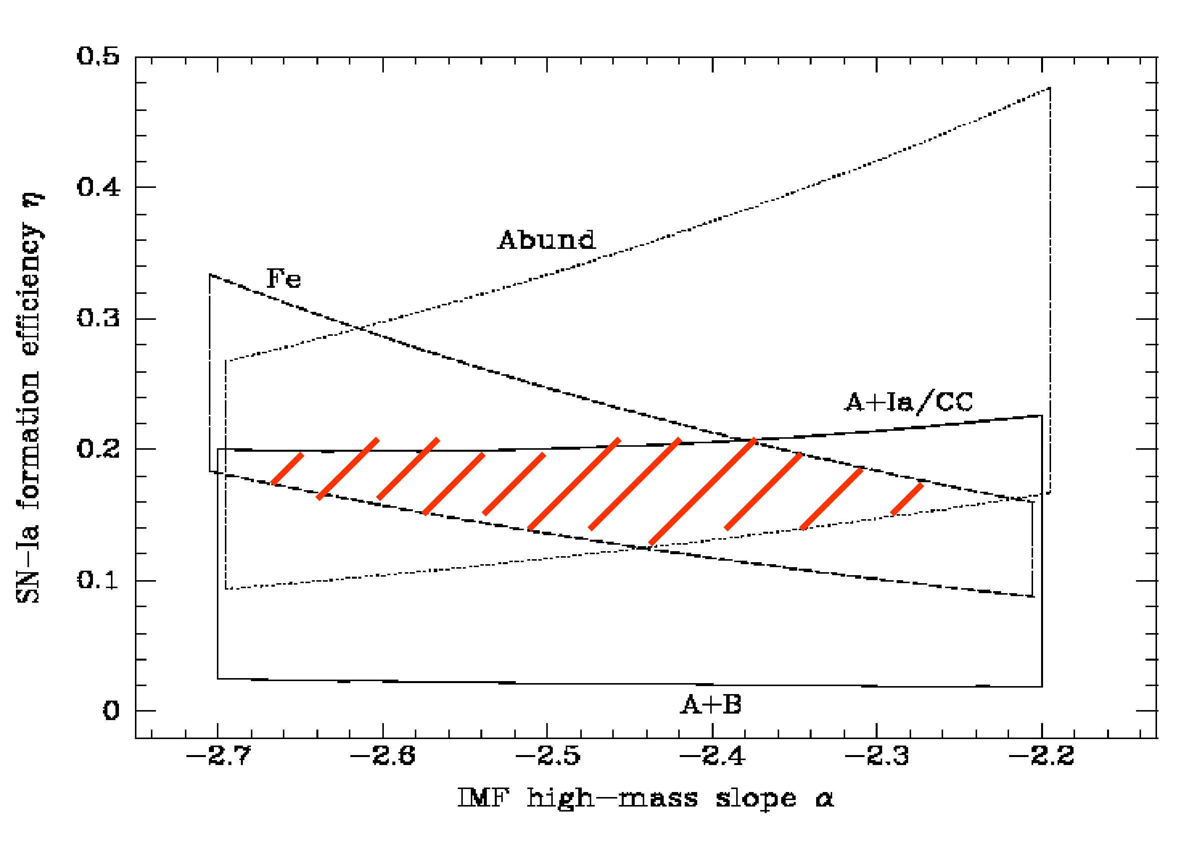
$$\eta_{\text{abnd}} = \frac{N_{\text{Ia}}}{N_{\text{CC}}} \frac{\int_8^{50} \phi(m)dm}{\int_3^8 \phi(m)dm} \sim 30\%$$

What fraction of all stars with m_{init}=3-8 M_{sun} go SN-Ia?

Maoz 2008

Method (1)	η(%) (2)	Reference (3)
Ia/CC	8 – 15	Mannucci et al. (2005)
B	5 – 7	Dahlen et al. (2004)
	8 – 10	Barris & Tonry (2006)
	6 – 18	Scannapieco & Bildsten (2005)
	3 – 9	Scannapieco & Bildsten (2005)
	1 – 1.5	Sullivan et al. (2006)
	3.8 – 4.3	Mannucci et al. (2006)
A	0.8 – 1.7	Mannucci et al. (2005)
	1 – 1.5	Sullivan et al. (2006)
	2 – 6	Sharon et al. (2007)
	2 – 3.5	Mannucci et al. (2007)
Fe	11 – 20	Lin et al. (2003)
Abund	14 – 40	De Plaa et al. (2007)

Maoz 2008



SN-Ia formation efficiency η
0.5
0.4
0.3
0.2
0.1
0
Abund
Fe
A+Ia/CC
A+B
−2.7
−2.6
−2.5
−2.4
−2.3
−2.2
IMF high−mass slope α

~10-20% of all m=3-8 Msun stars explode as SNe-Ia
……but……..

÷ 0.7-1 are in binaries;

÷ 0.15–0.3 have secondaries that are not too small

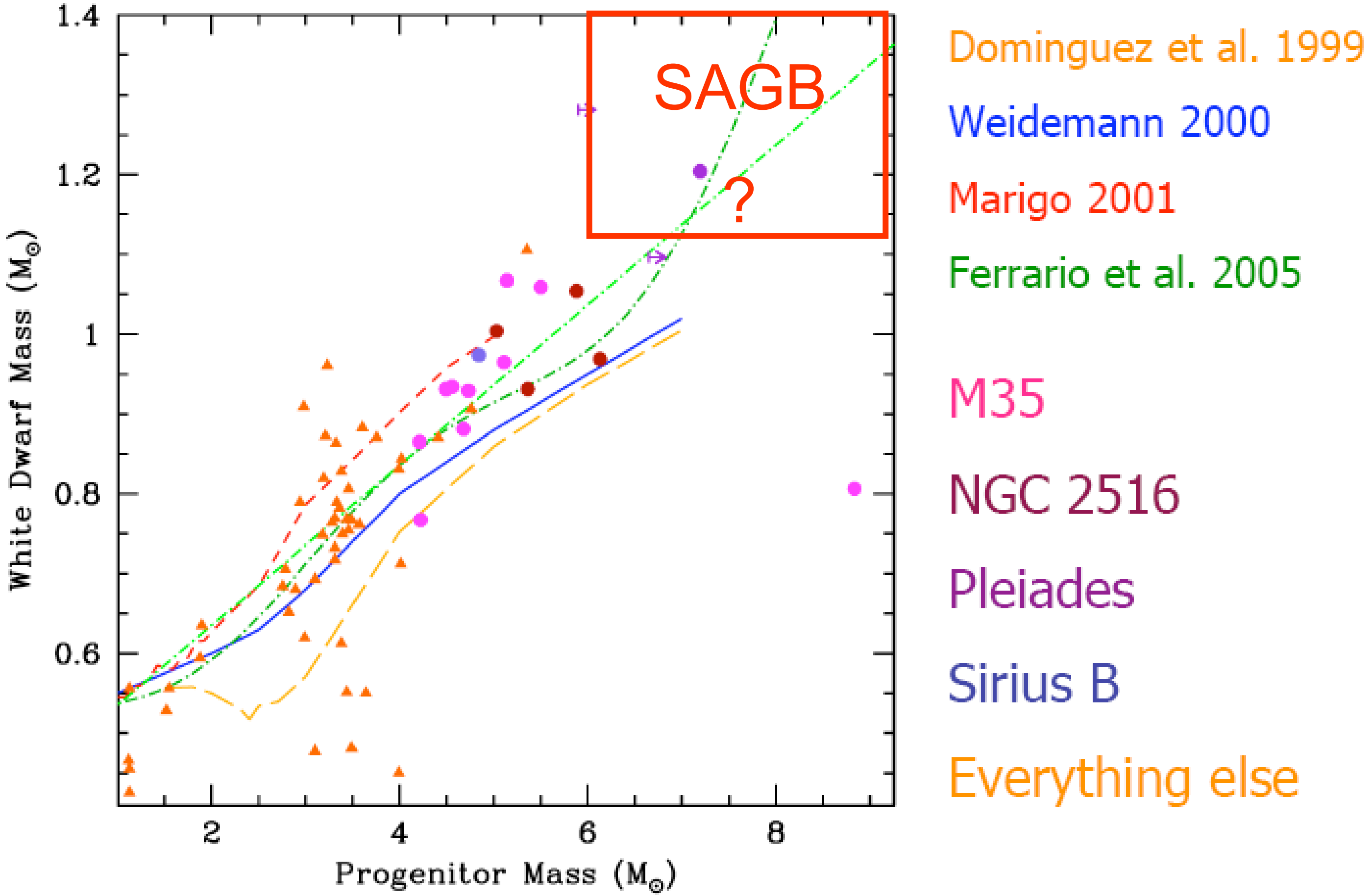
÷ 0.25–0.5 have close enough separations

÷ 0.5 : every binary can make just 1 SN-Ia!

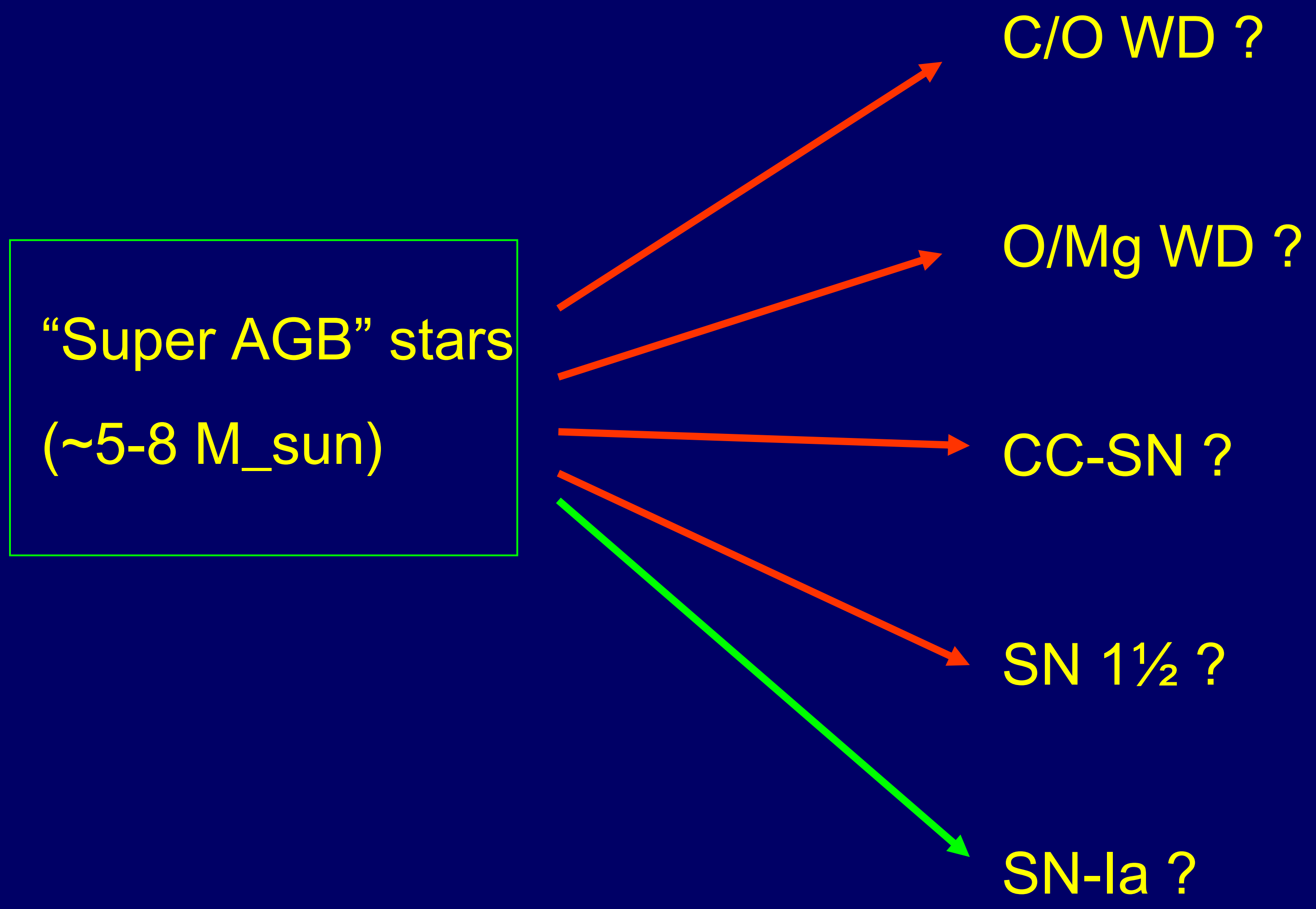
~100% to 1000 % of close, intermediate-mass, binaries end up as SNe-Ia !

A heretical idea:

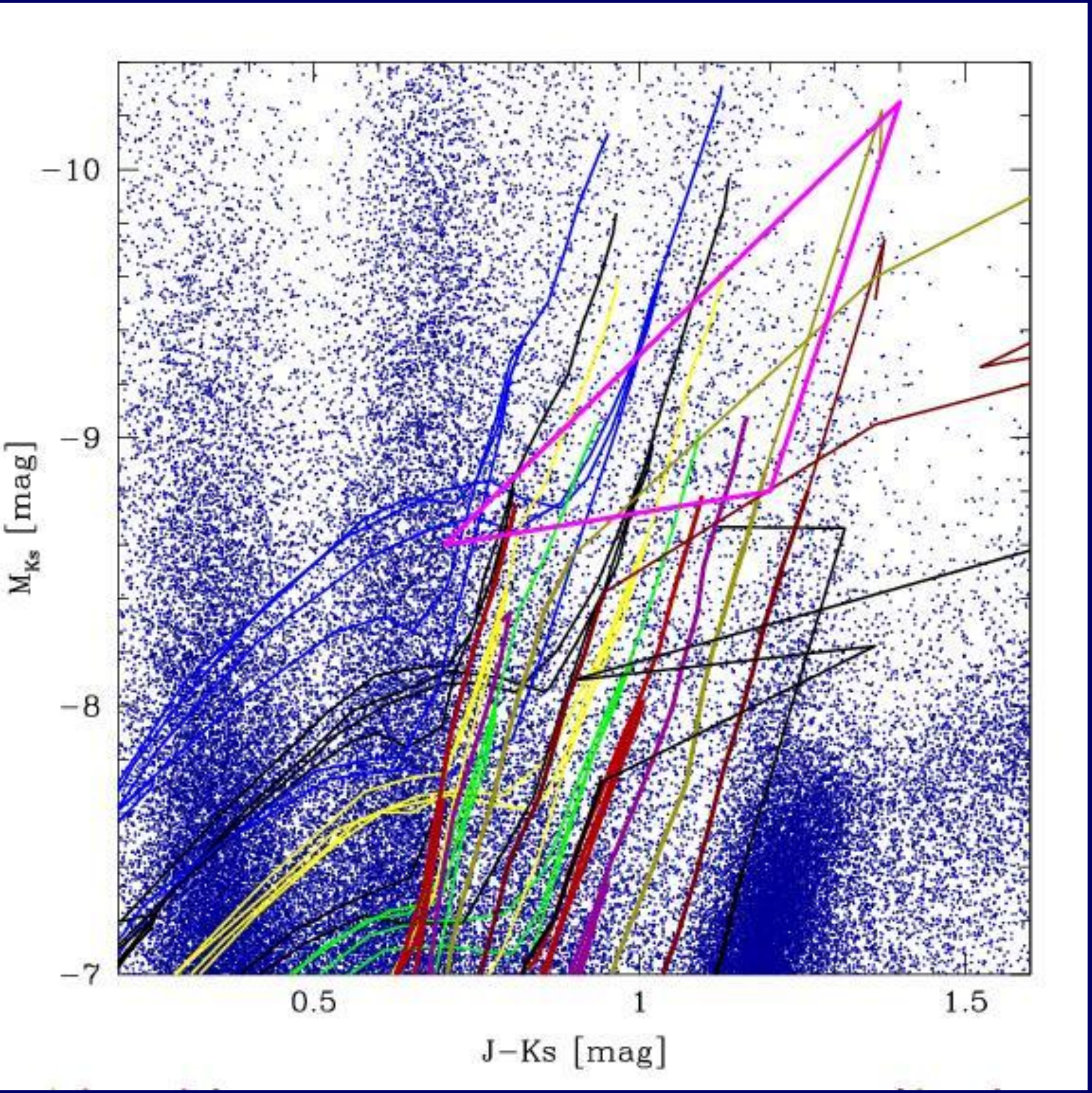
Could SNe-Ia have single-star progenitors?



K. Williams (2008)



"Super AGB" stars
(~5-8 M_sun)
C/O WD ?
O/Mg WD ?
CC-SN ?
SN 1½ ?
SN-Ia ?


−10
−9
−8
−7
0.5
1
1.5
M_{Ks} [mag]
J−Ks [mag]

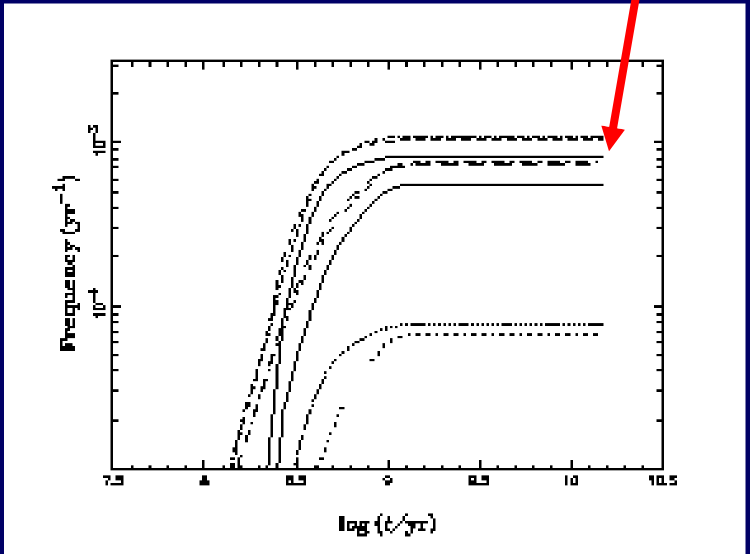
Binary population synthesis predictions:

Yungelson, Tutukov, Livio: DD: only 14% of close 3-8 Msun binaries go SNIa

SD: ~1%

Han & Podsiadlowski 2004: SD MS channel: B=(1-2) x 10^{-4} / Msun

Hachisu RG channel: negligible



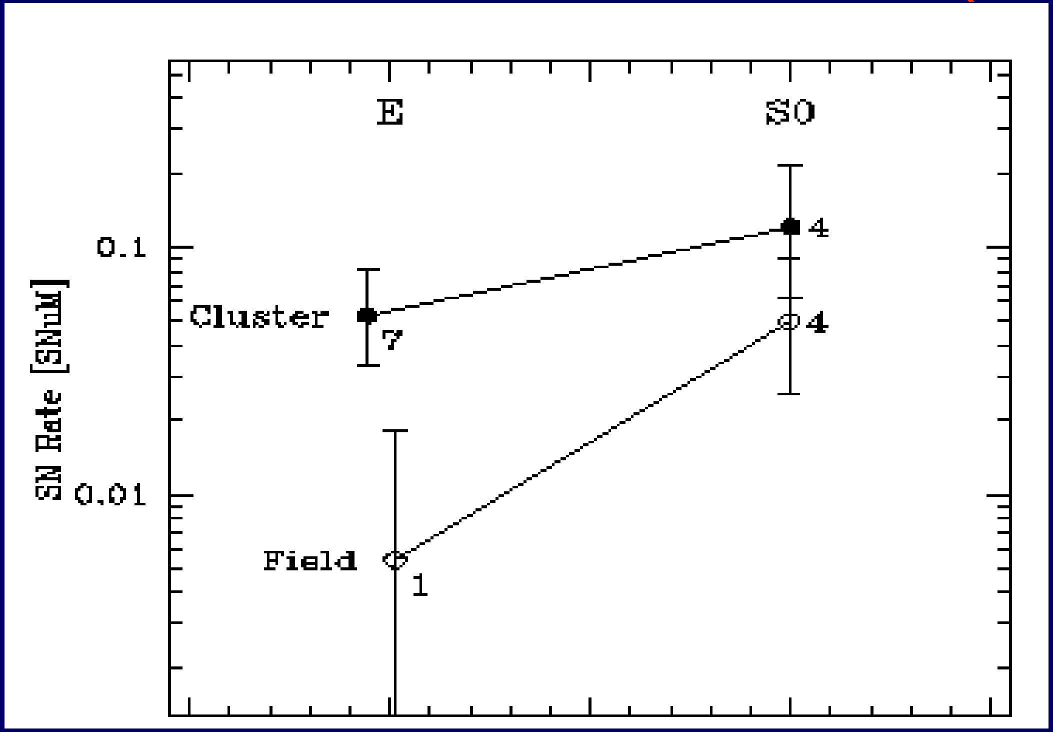
Dependence of SN rate on environment?

(Mannucci et al. 2007):

E+S0 $SNR_{Ia}(z=0)=0.038^{+0.014}_{-0.012}$ SNuM (Mannucci et al. 2005)

0.066 SNuM in clusters (11 SNe)

0.019 SNuM in field (5 SNe)



How to measure a SN rate?

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

SN rate per galaxy

Visibility time ("control time")

$$R_M = \frac{N_{\mathrm{SN}}}{\sum_i m_i t_i},$$

SN rate per unit mass

Stellar mass in each galaxy