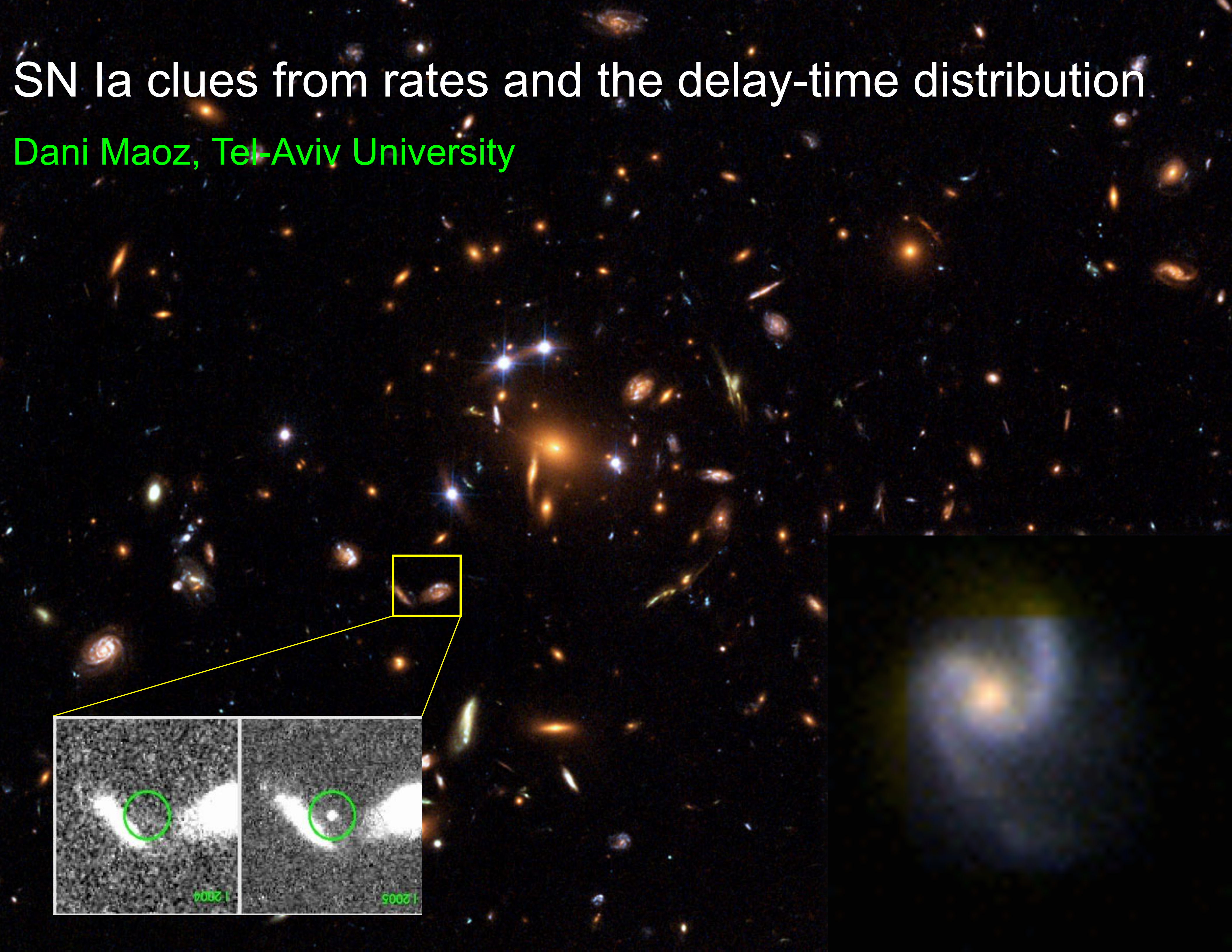
SN Ia clues from rates and the delay-time distribution

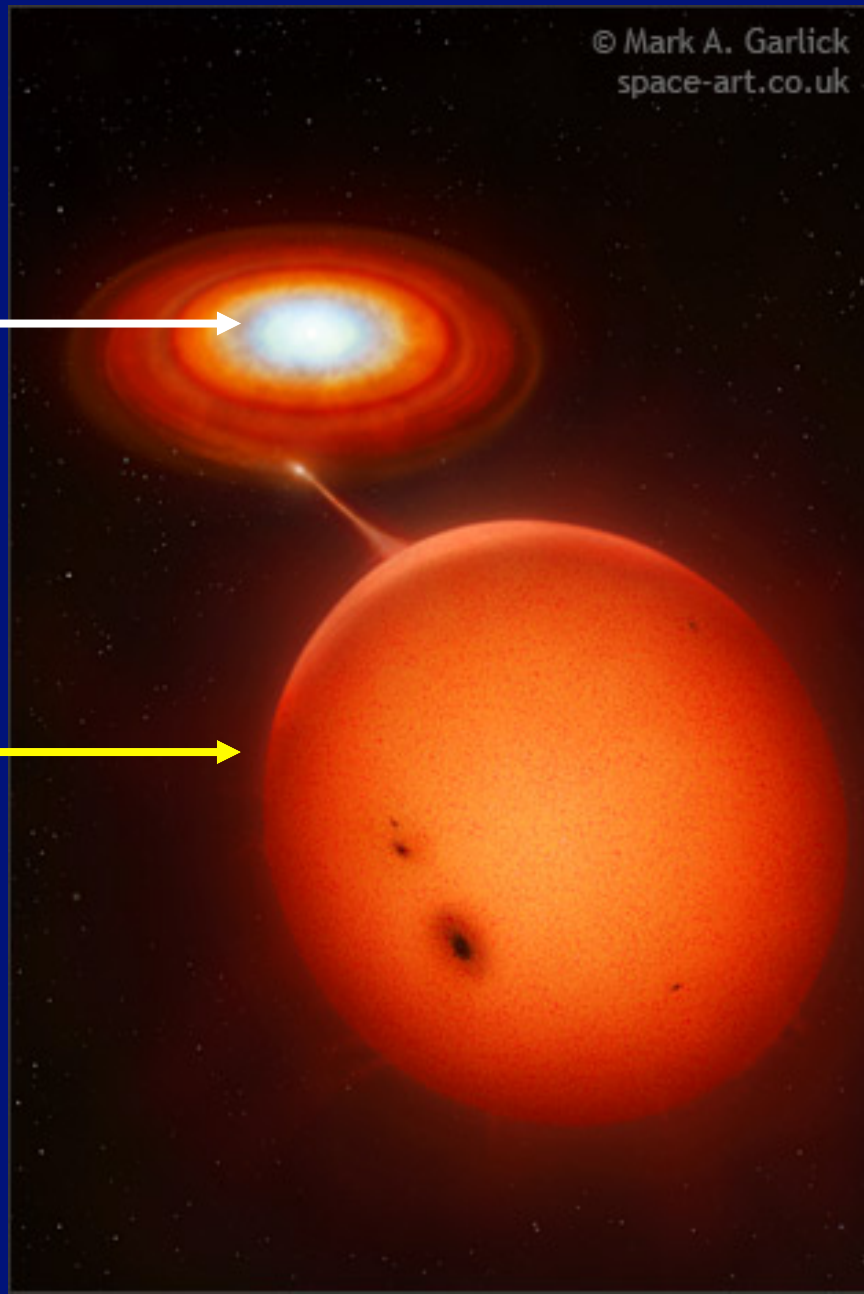
Dani Maoz, Tel-Aviv University



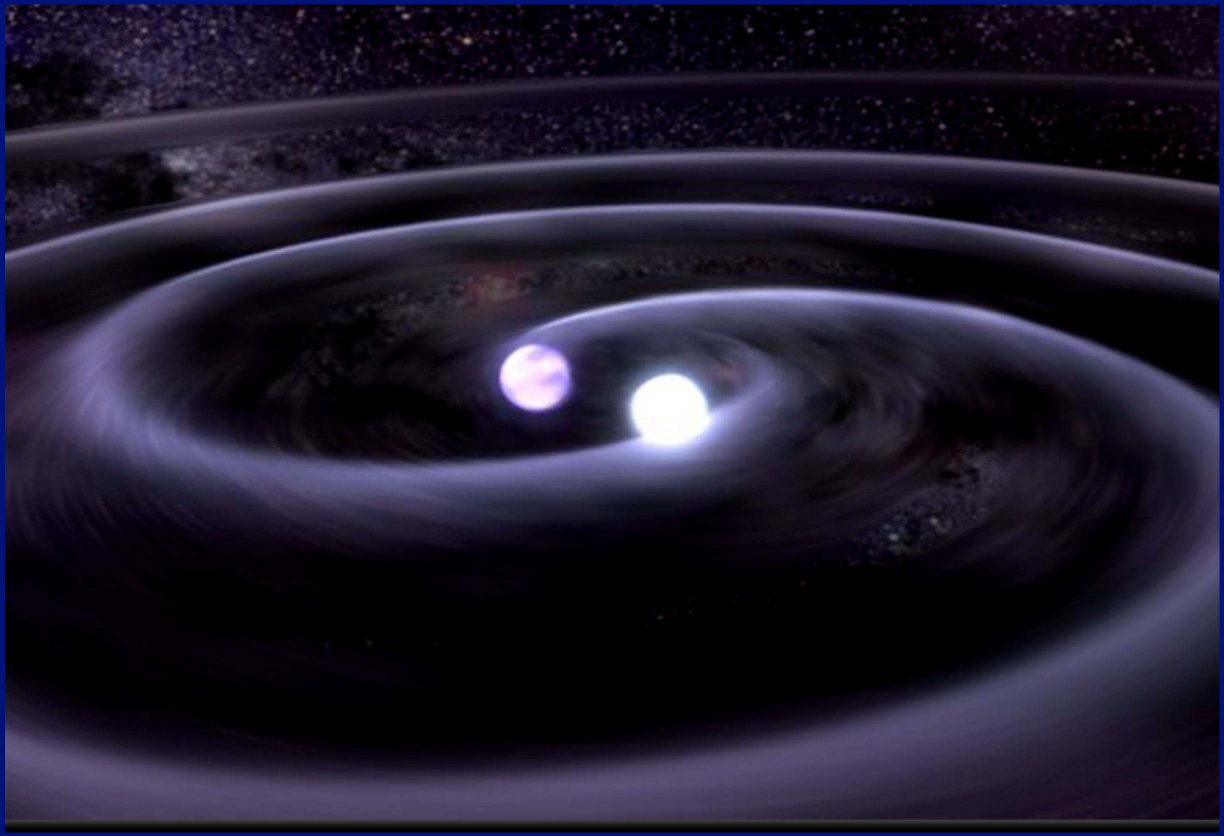
“single degenerate” (“SD”) (Whelan & Iben 1974)

WD

Main sequence, subgiant, red-giant, or “helium star”

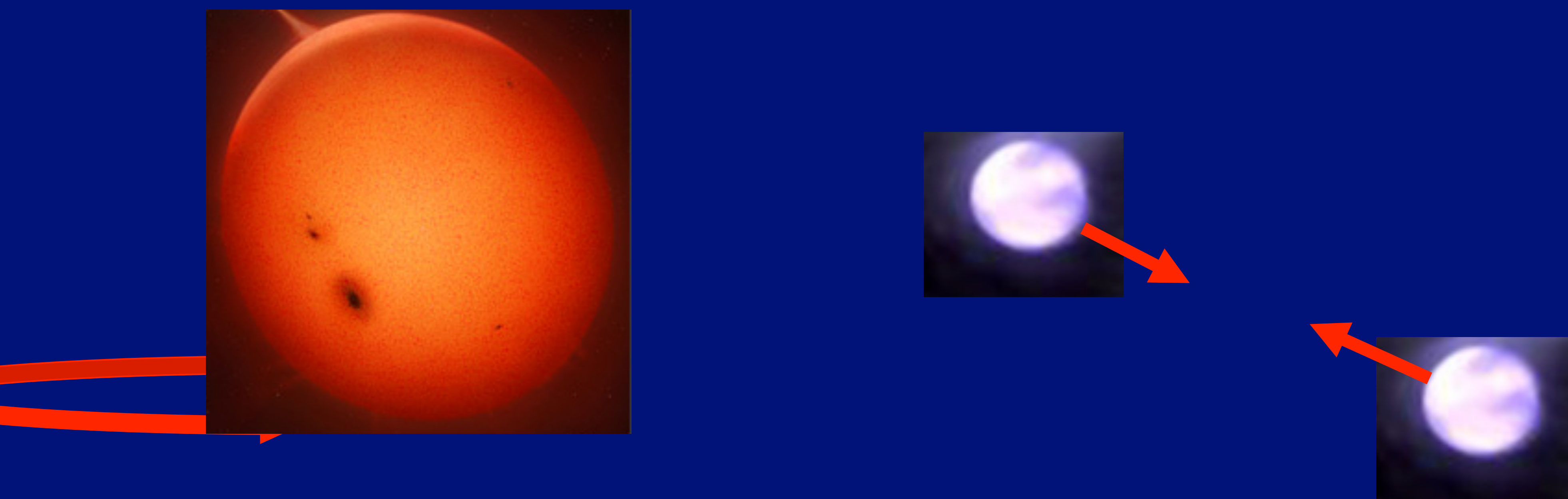


“double degenerate” (“DD”) (Webbink 1984; Iben & Tutukov 1984)



Also: “collisional double degenerate”

(Benz+, Hawley+, Loren-Aguilar+, Raskin+, Rosswog+, Thompson, Katz & Dong, Kushnir+, Garcia-Senz+…)



Also: “core degenerate” (Soker+) merger + spinup/spindown

Measuring SN Rates

Can give clues to progenitors

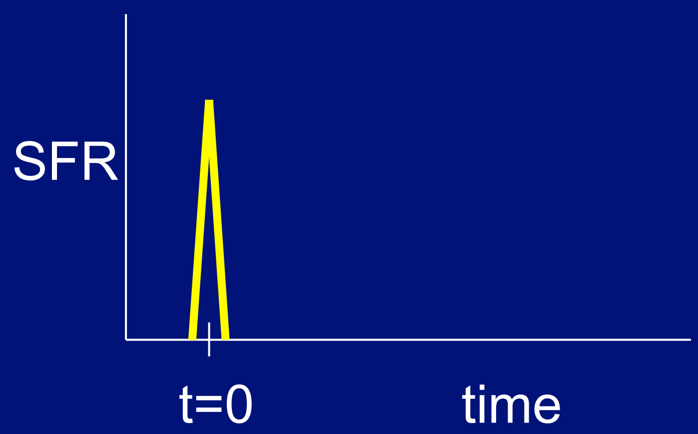
SN Ia "delay time distribution" (DTD):

=

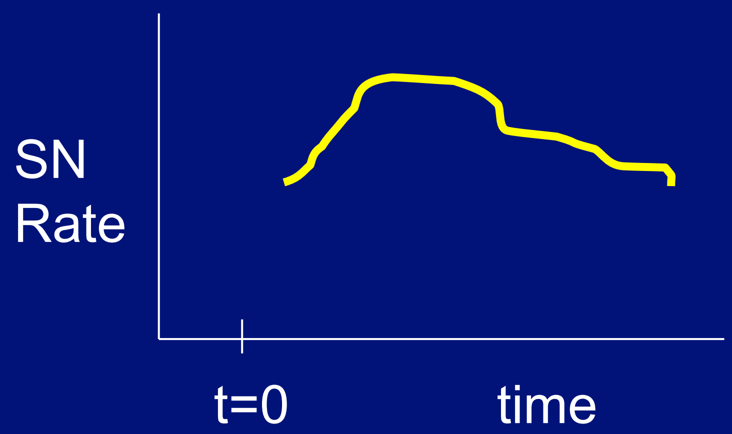
the hypothetical SN Ia rate vs. time following a short burst of star formation.

Different progenitor scenarios predict different DTD

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

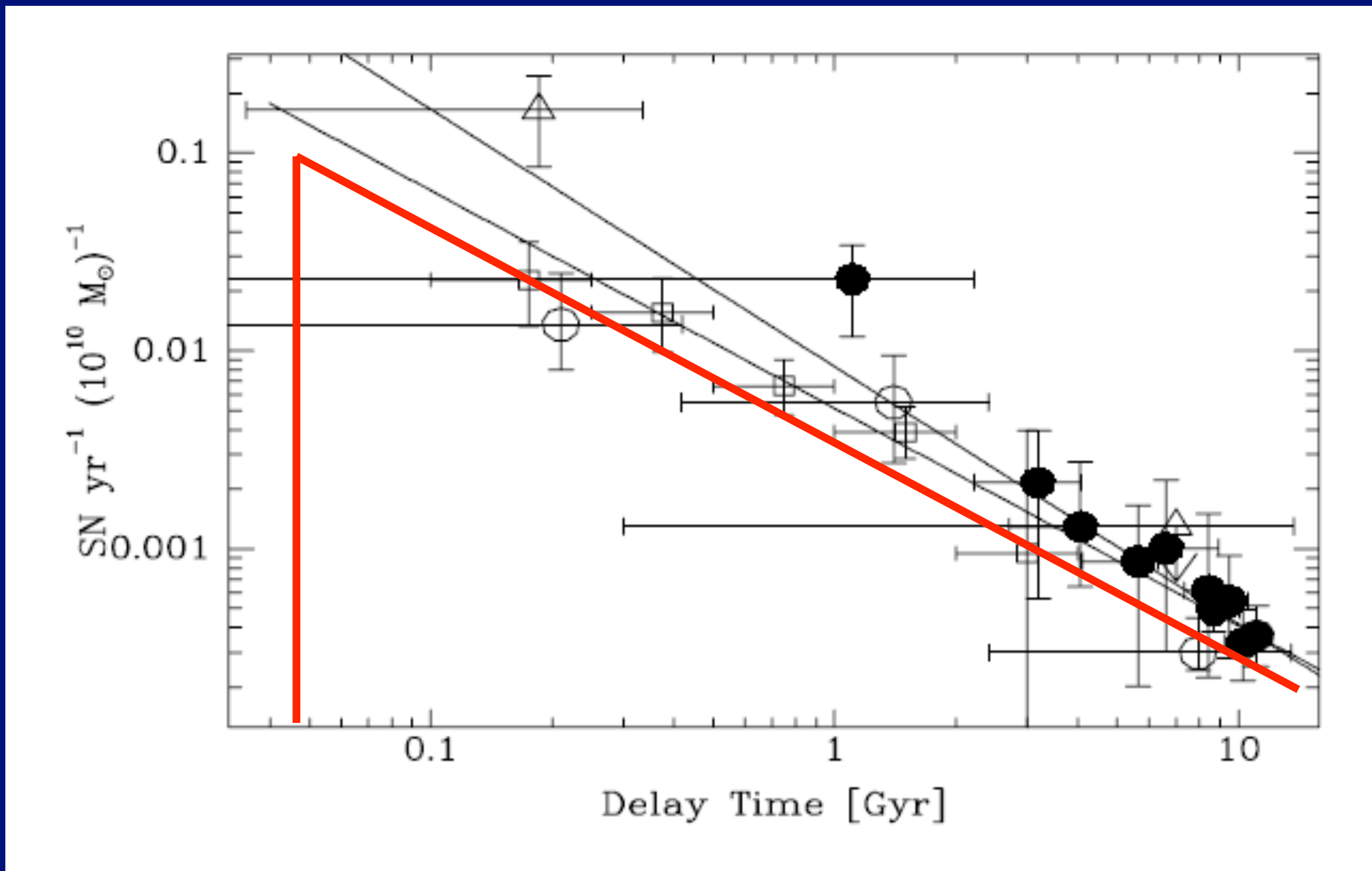
$$\frac{dN}{da} \sim a^{\epsilon},$$

then the event rate will be

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

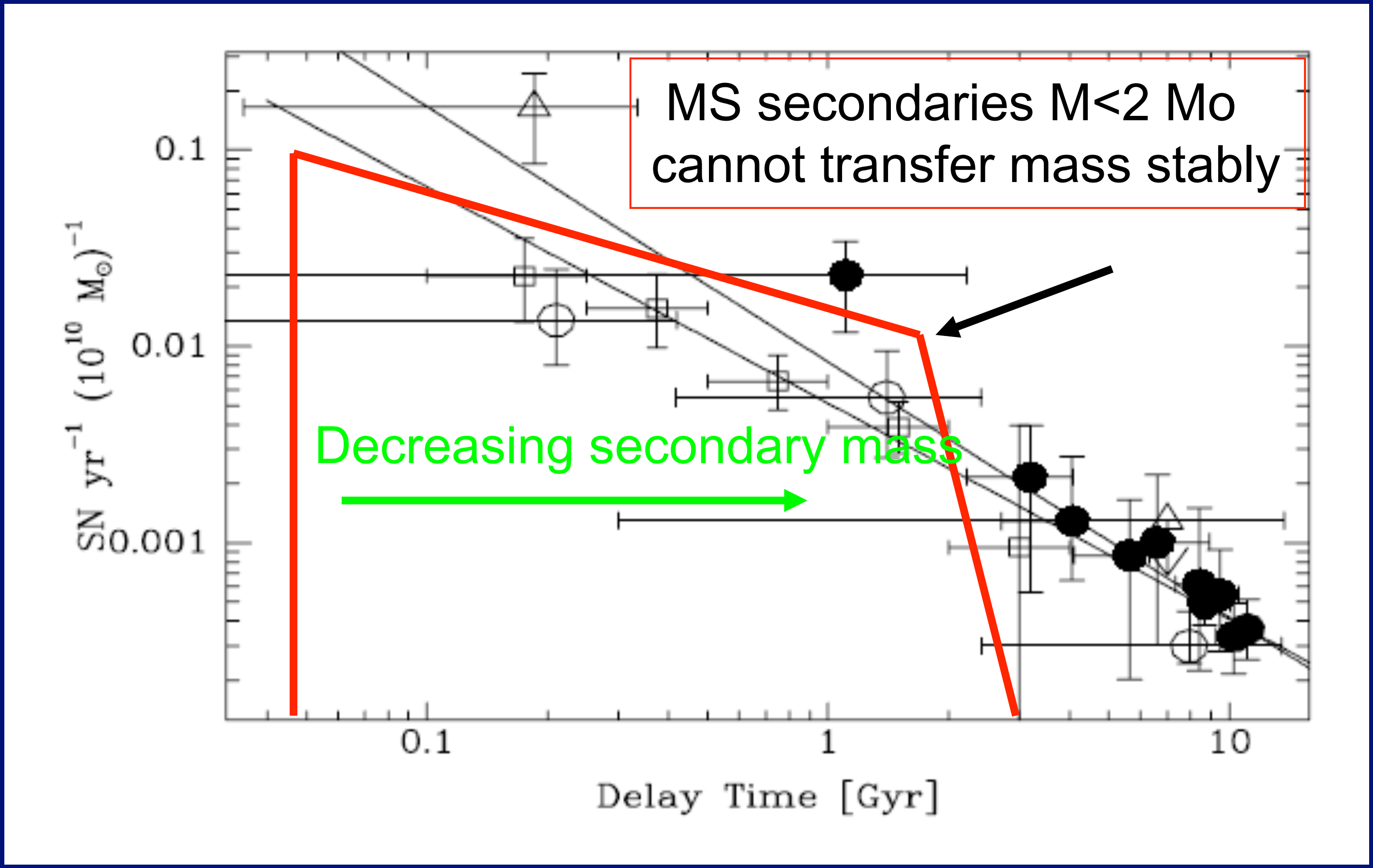
DTD ~ t^{-1} expected generically

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



similarly:

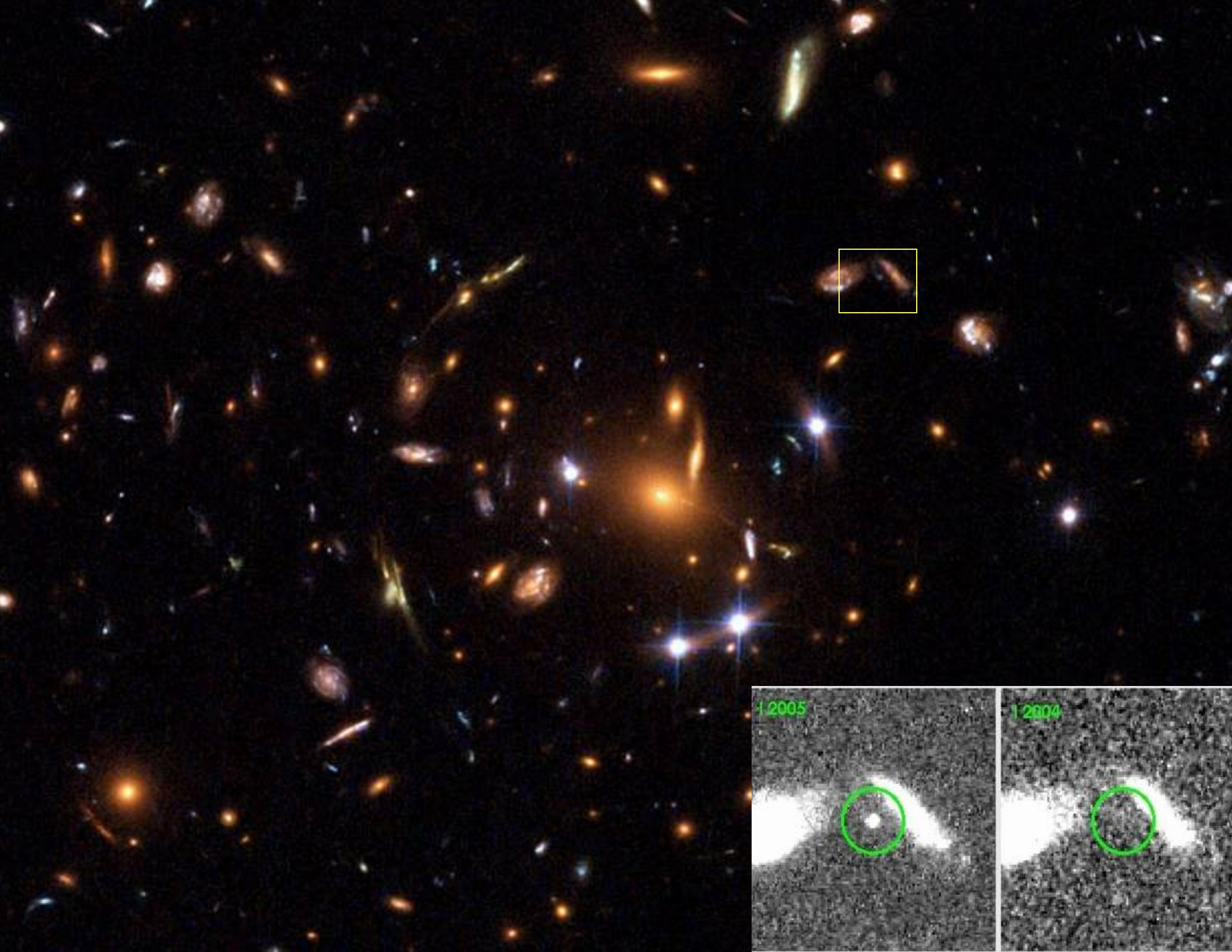
single-degenerate: DTD cutoff at few Gyr



Recovering the delay time distribution (many different ways to do it)

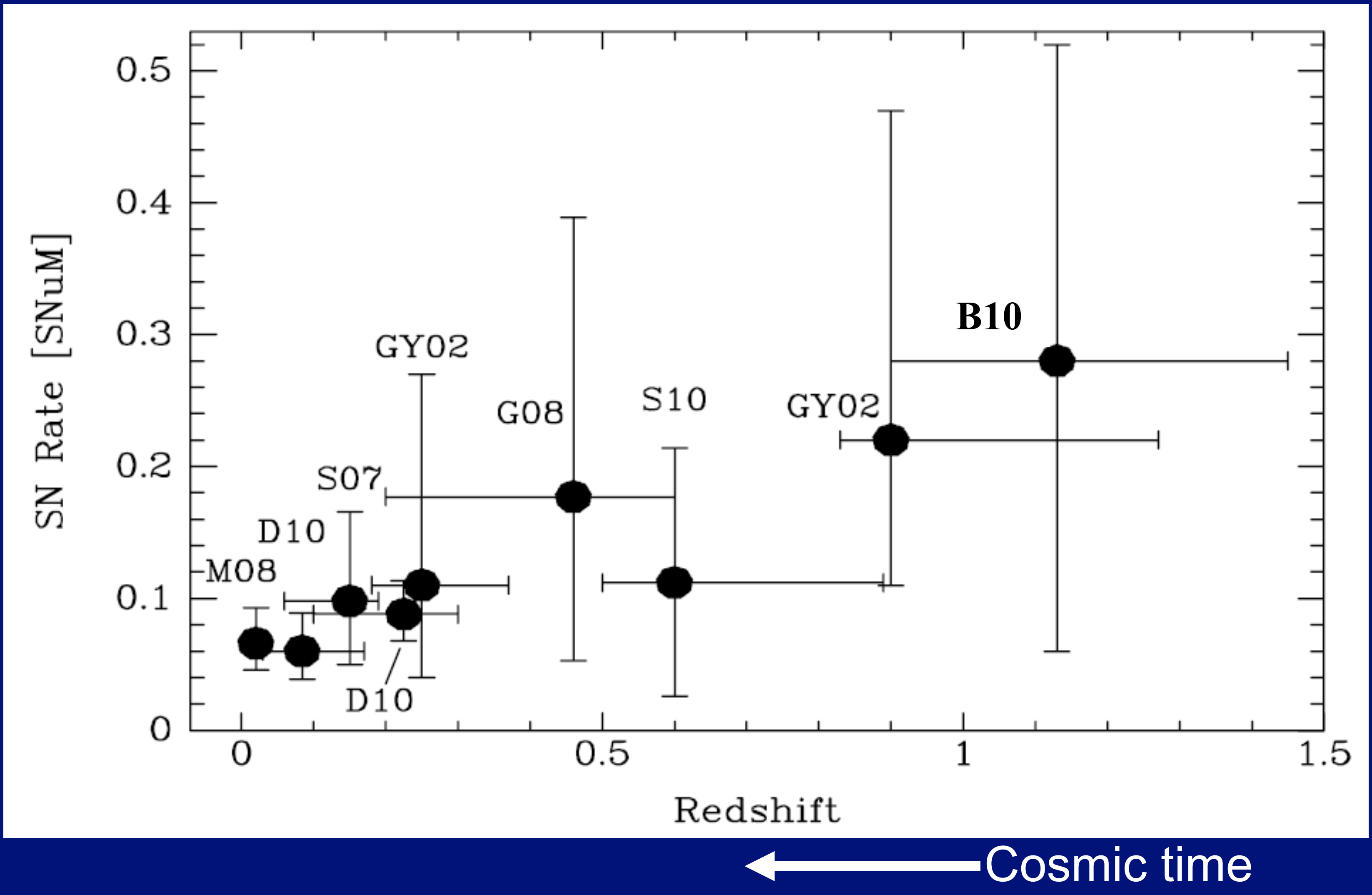
e.g. SN rates in galaxy clusters

SDSS 1004+4112 z=0.68 Sharon et al. (2010)



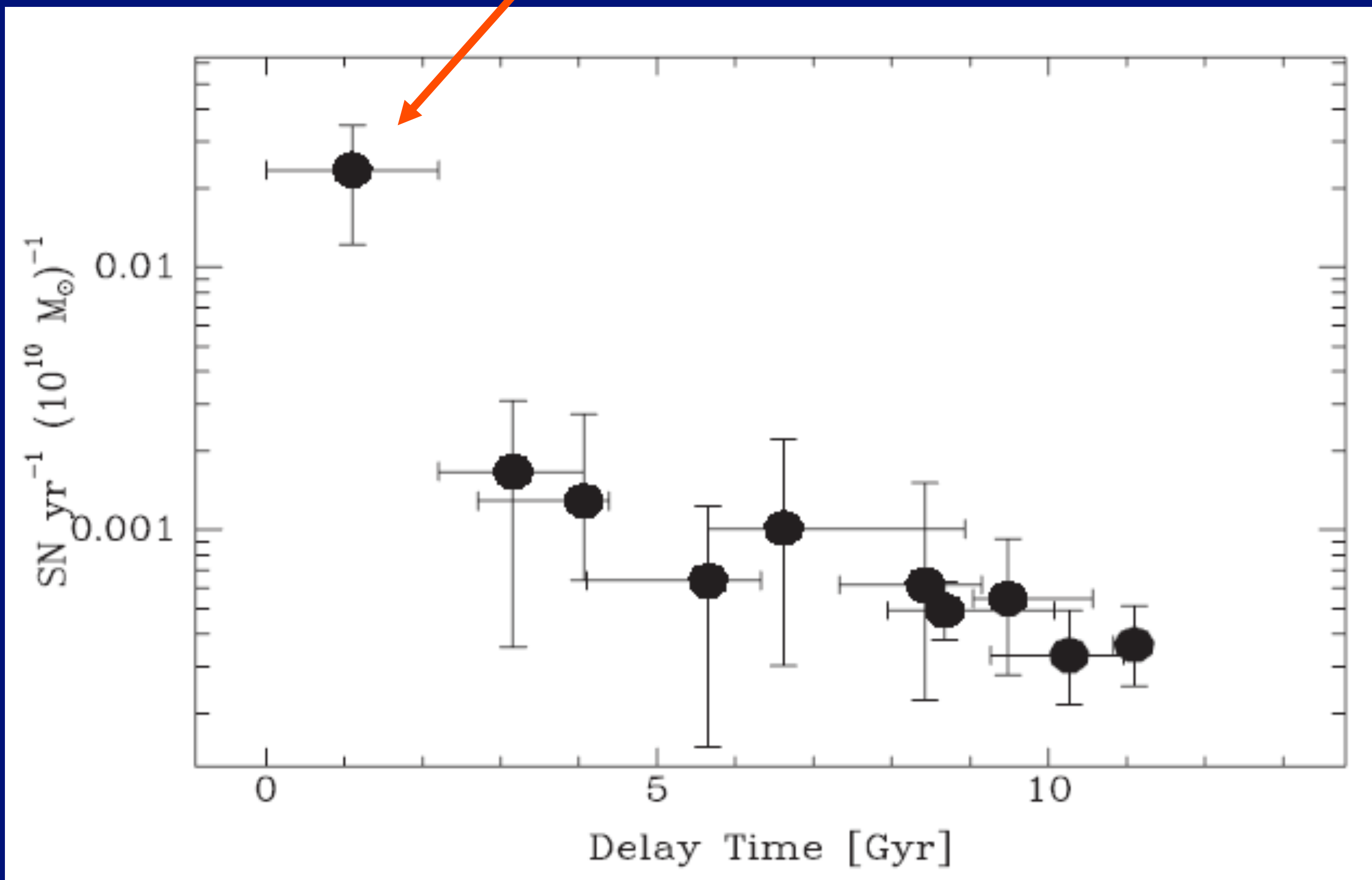
1 2005
1 2004

The SN rate vs. redshift in galaxy clusters



Maoz, Sharon, Gal-Yam (2010)

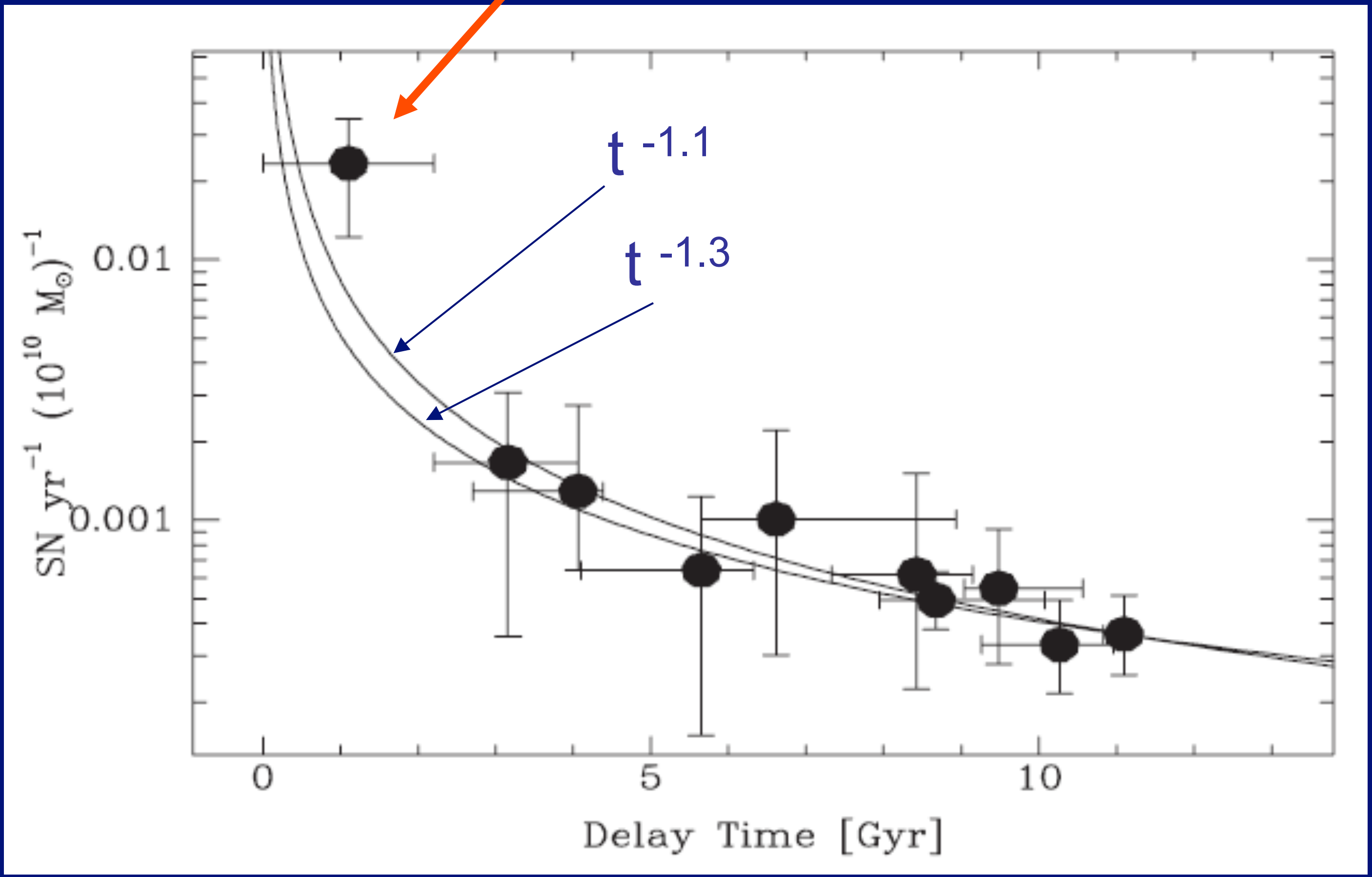
Time-integrated # of SNe-Ia must produce observed mass of Fe in clusters (minus mass from CC-SNe)



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)

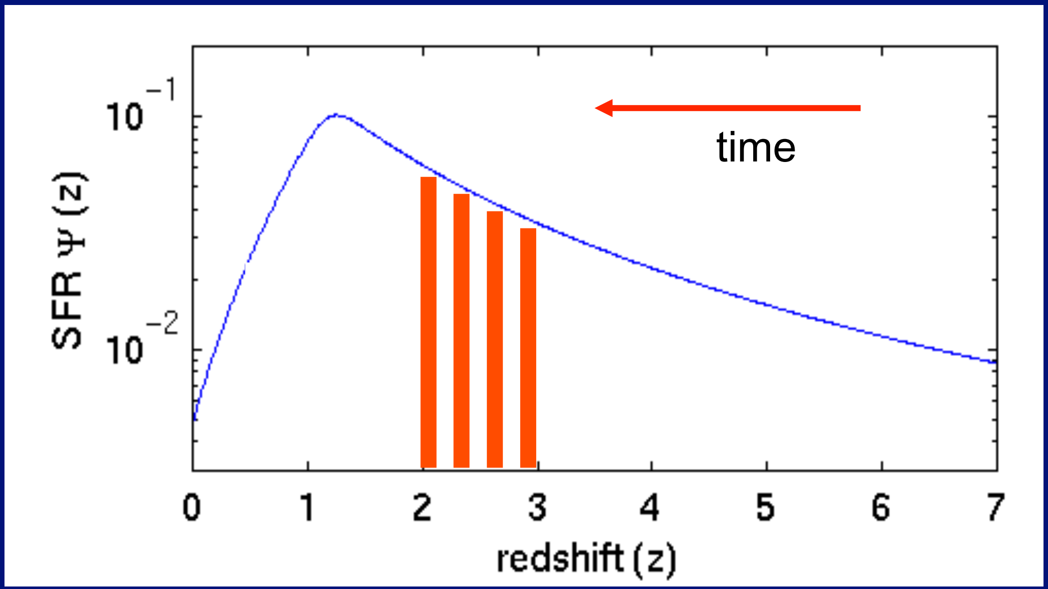
SN rates in galaxy clusters + iron/star mass ratio

How to recover the delay time distribution

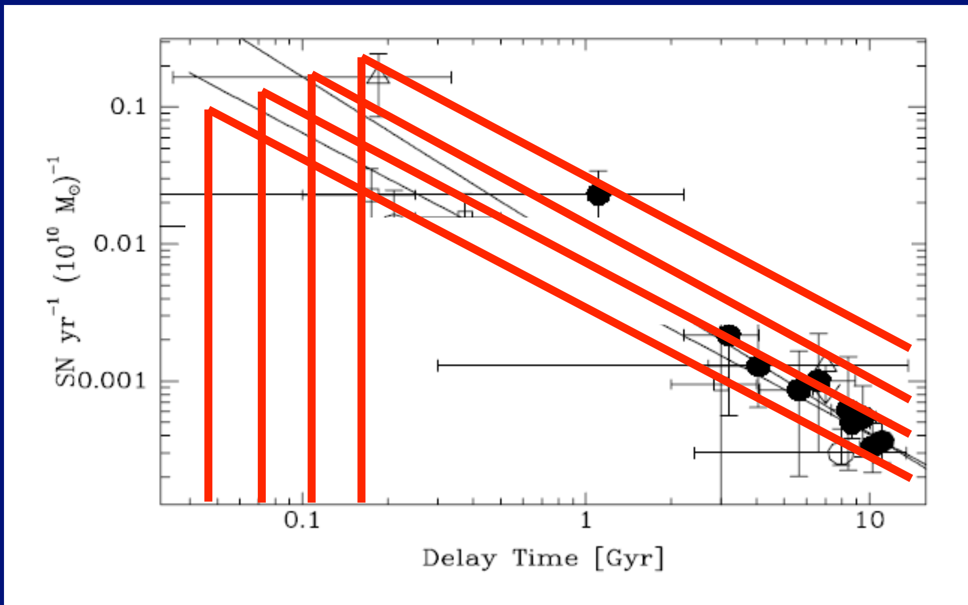
or… volumetric SN rates vs. redshift in field, compared to cosmic SFH

Star-formation history (z)

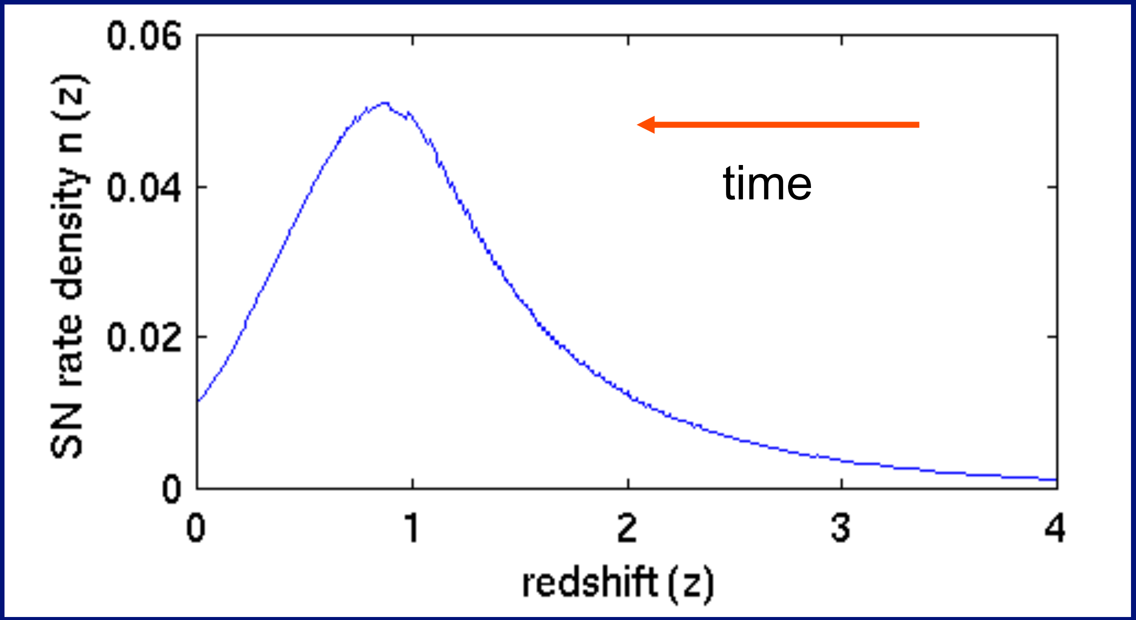
SN delay time distribution (t)



⊗



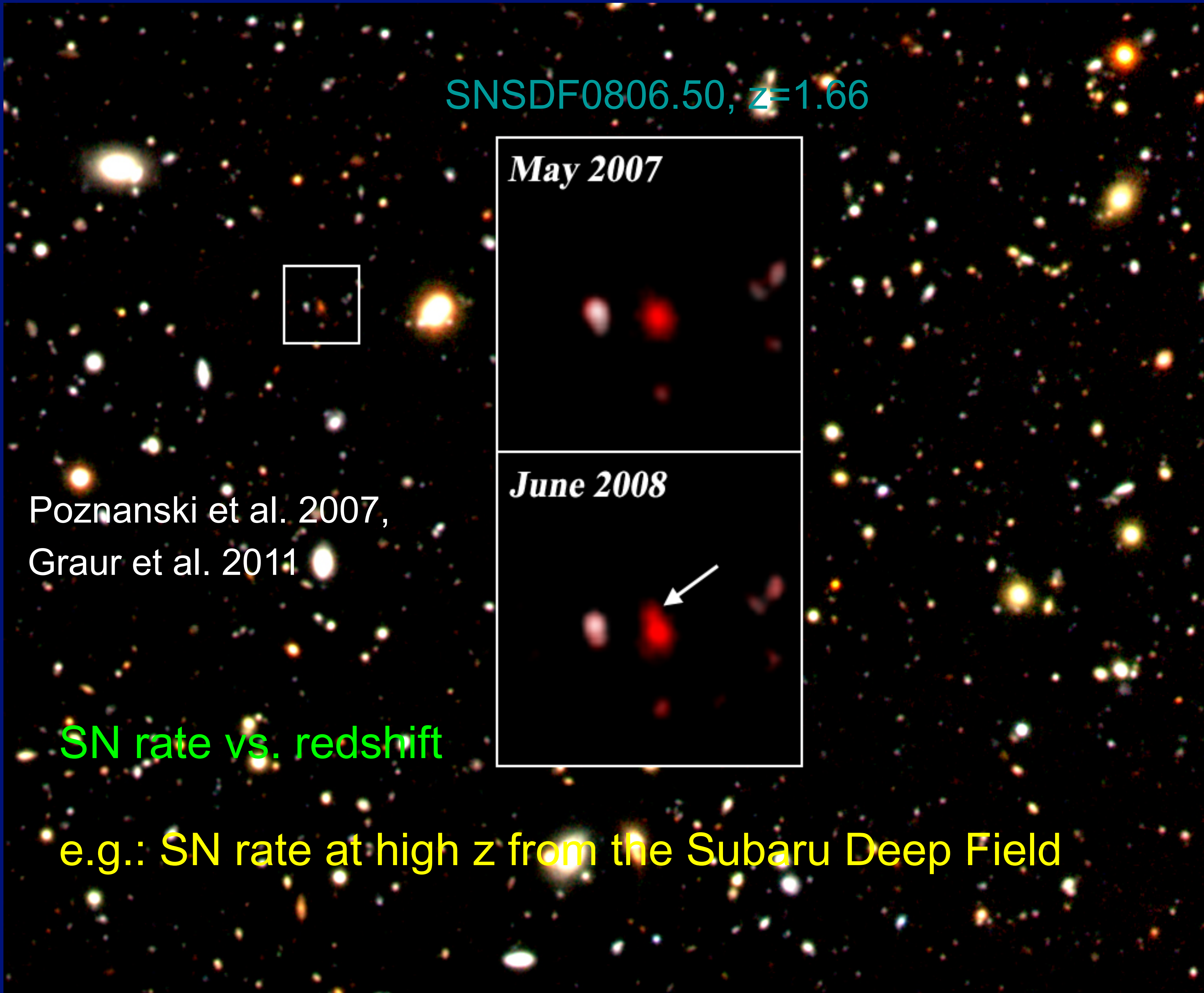
=



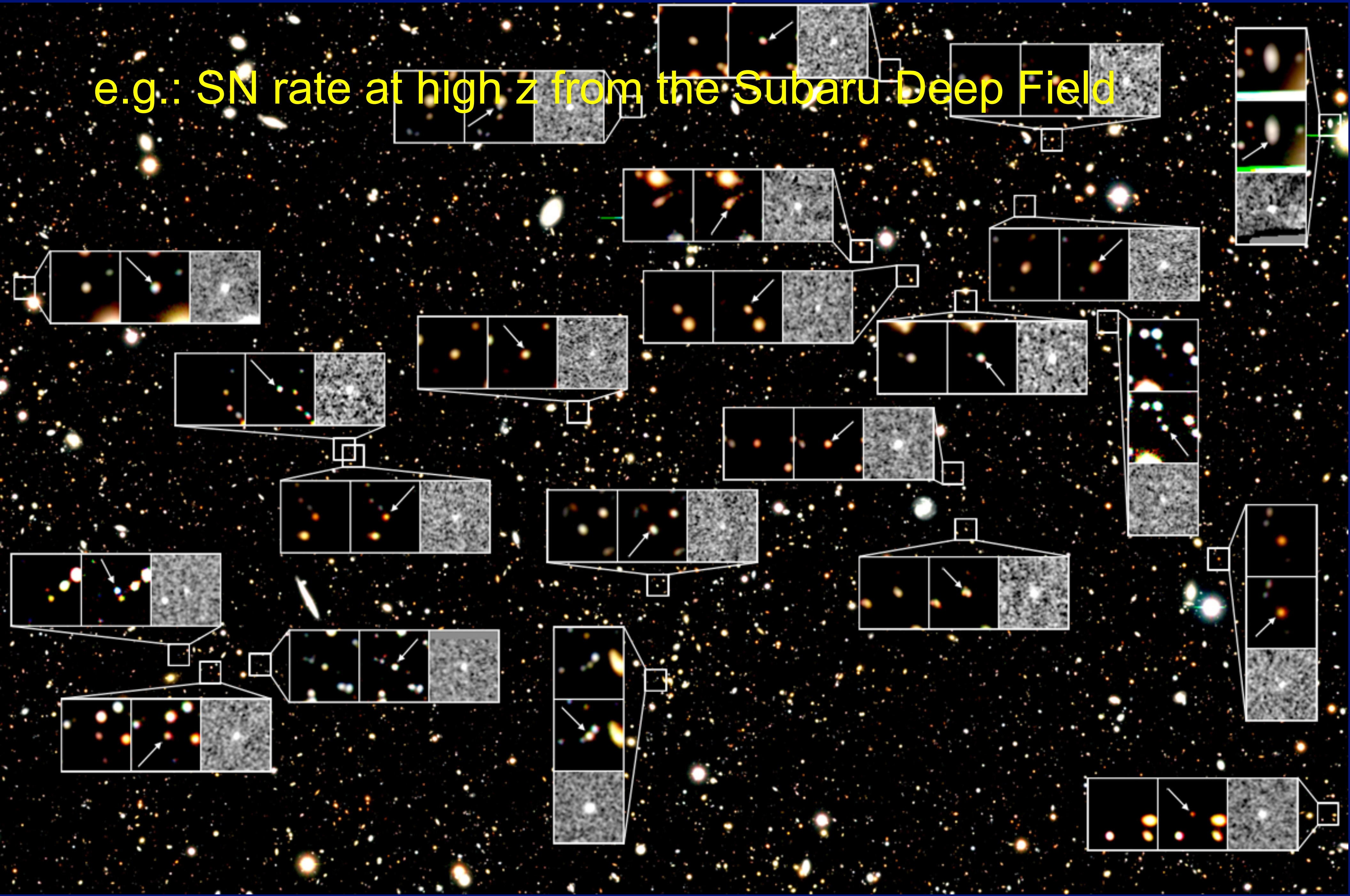
SN rate (z)

SN rate SFH delay time dist.

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

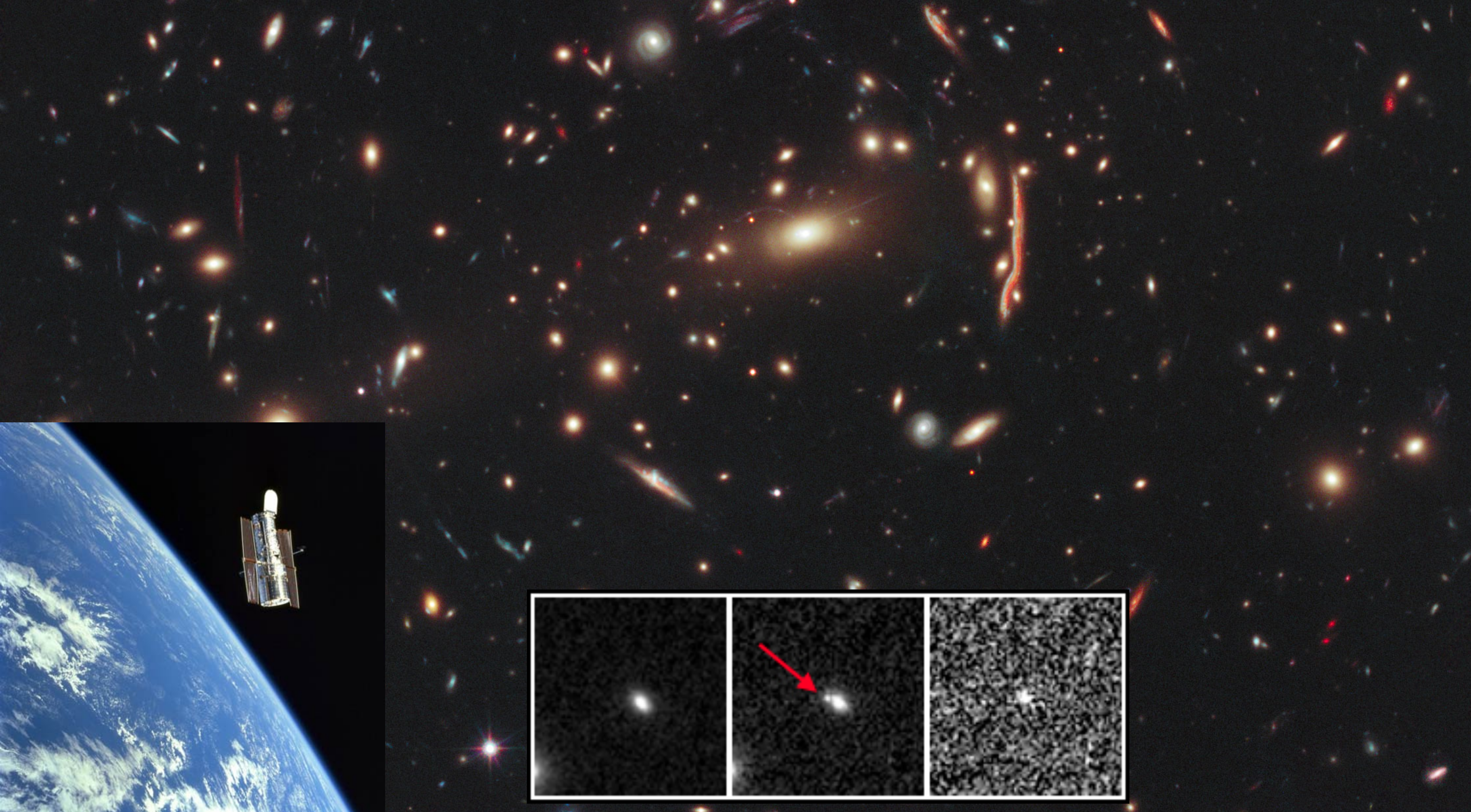

SNSDF0806.50, z=1.66
May 2007
June 2008
Poznanski et al. 2007,
Graur et al. 2011
SN rate vs. redshift
e.g.: SN rate at high z from the Subaru Deep Field

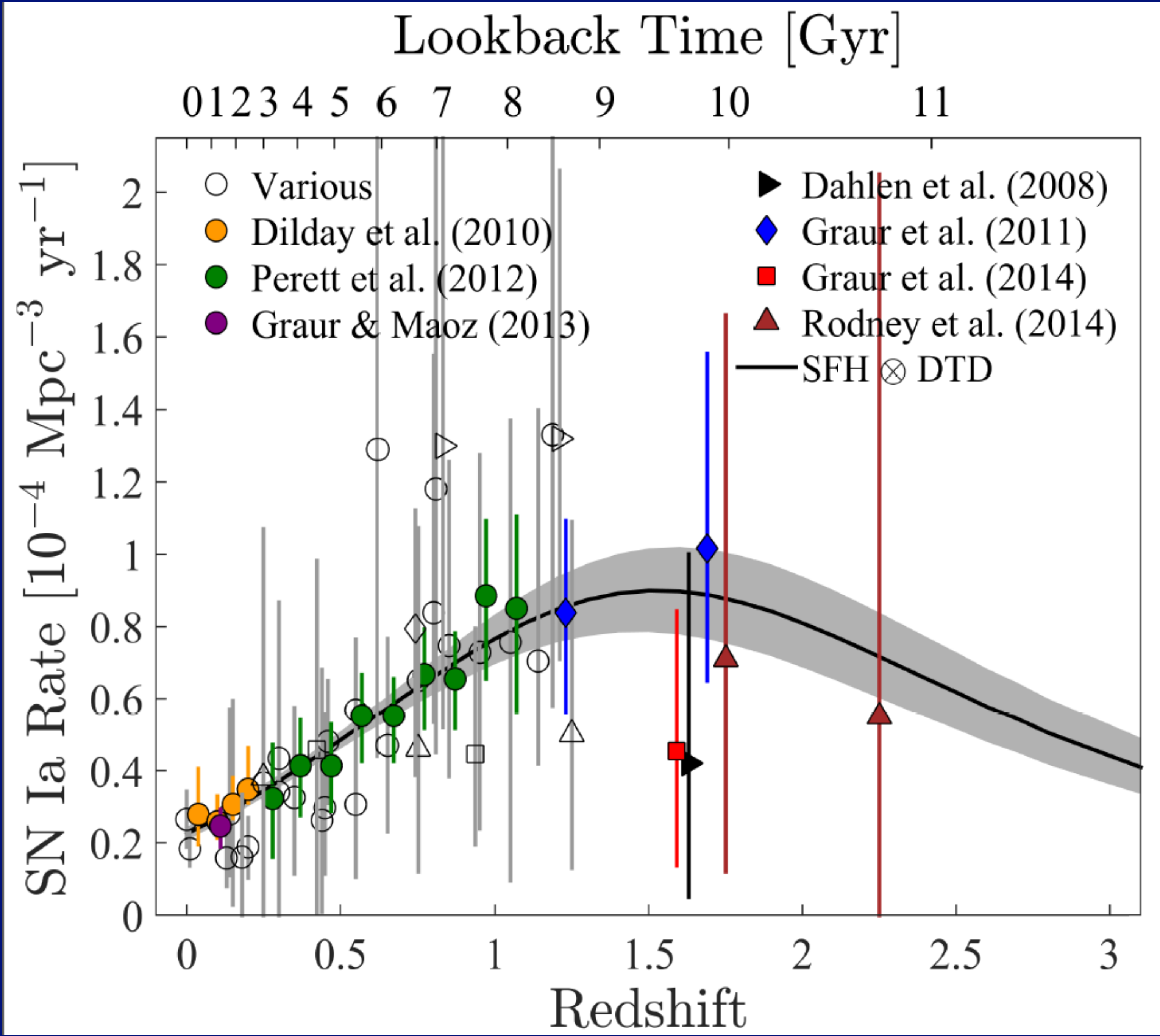
SN rate vs. redshift



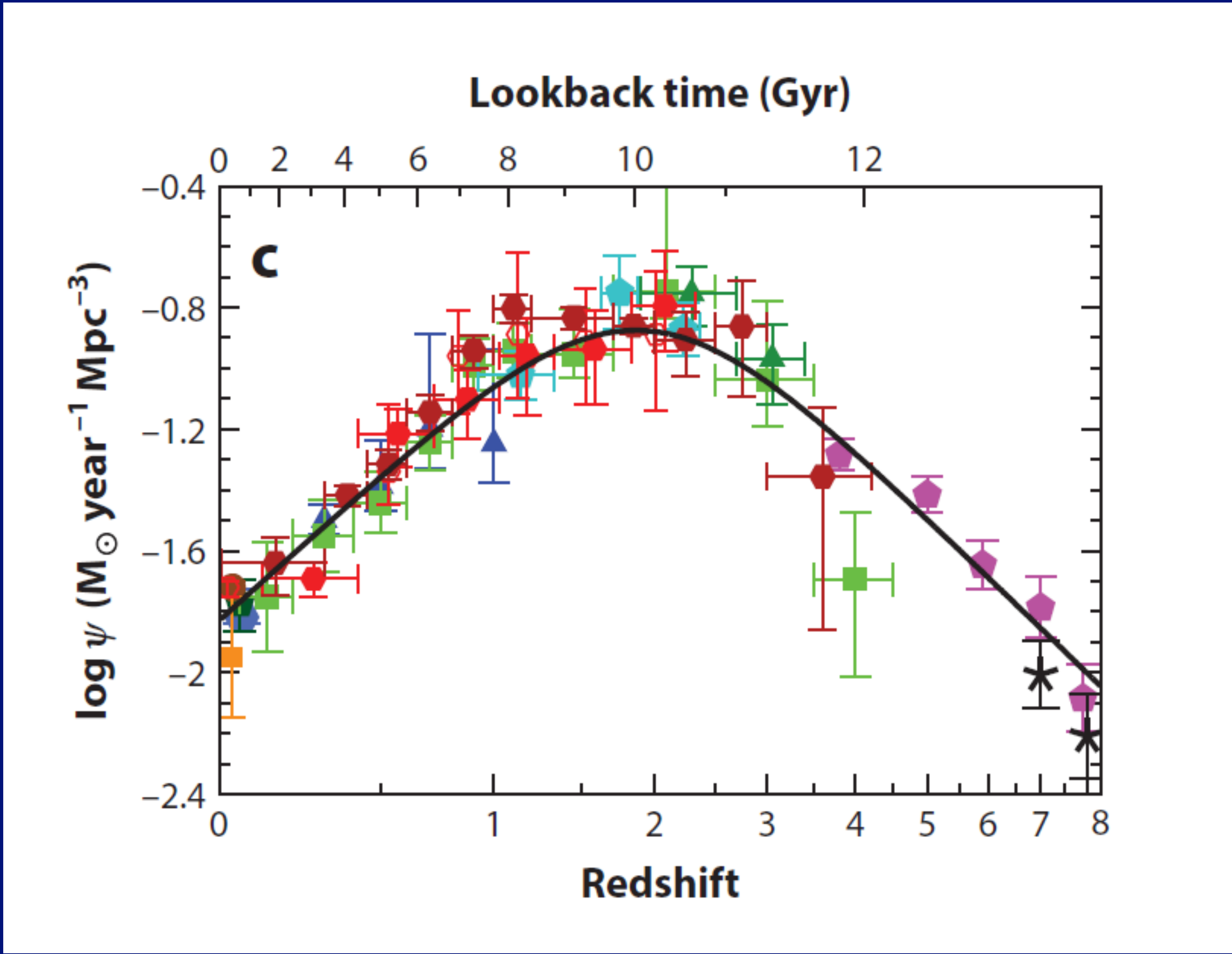
SN rates out to z=2 and beyond with HST CLASH/ CANDELS

Graur + 2014, Rodney+2015

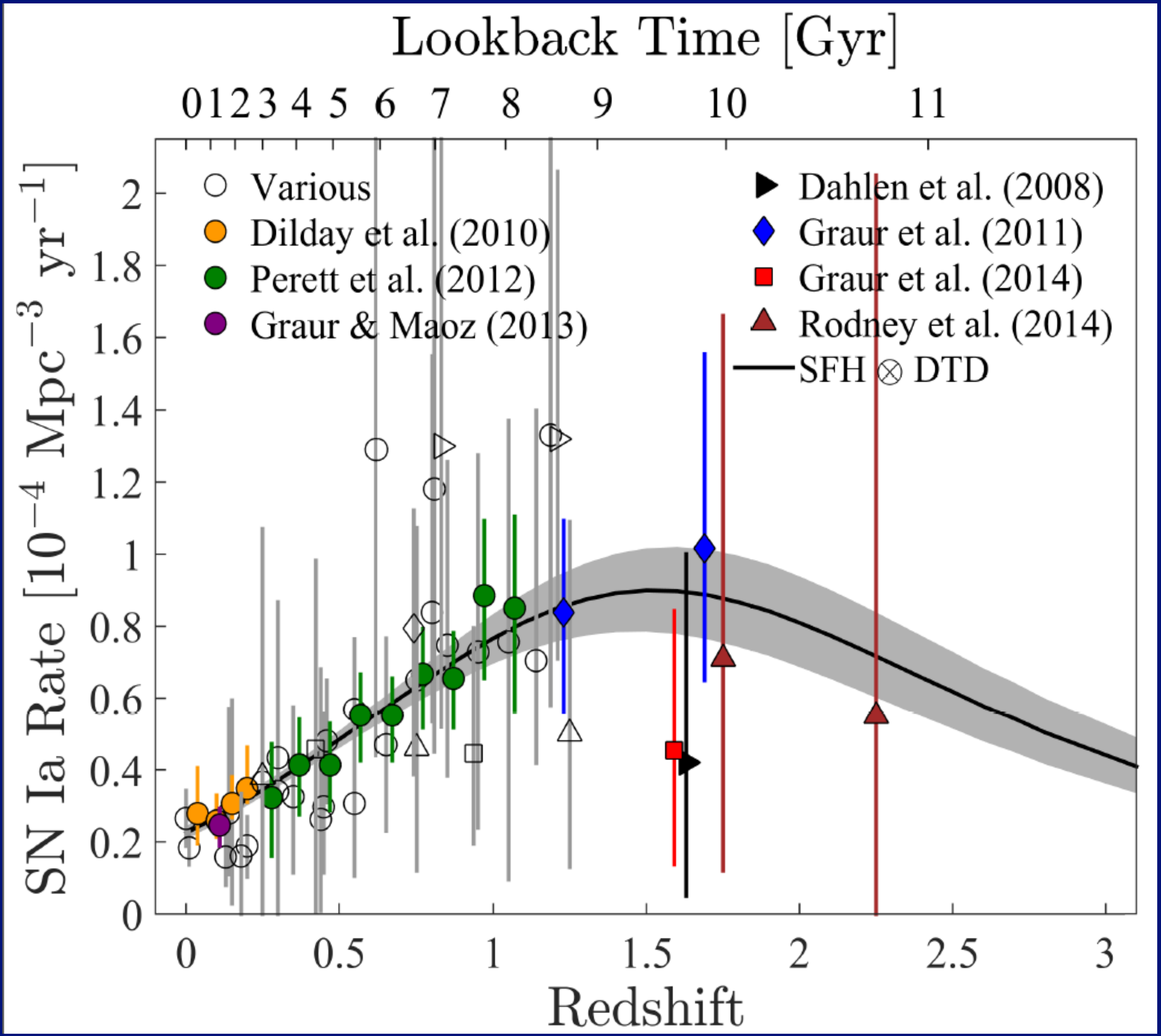




Lookback Time [Gyr]
0 1 2 3 4 5 6 7 8 9 10 11
SN Ia Rate [10^{-4} Mpc^{-3} yr^{-1}]
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
Various
Dilday et al. (2010)
Perett et al. (2012)
Graur & Maoz (2013)
Dahlen et al. (2008)
Graur et al. (2011)
Graur et al. (2014)
Rodney et al. (2014)
SFH ⊗ DTD
0 0.5 1 1.5 2 2.5 3
Redshift



Madau & Dickinson 14



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Graur et al. (2014)
Rodney et al. (2014)
SFH ⊗ DTD
0 0.5 1 1.5 2 2.5 3
Redshift

How to recover the delay time distribution

or… SN Rates vs. individual galaxy star-formation histories

SN rate

SFH

delay function

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

True also in an individual galaxy!

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

expect. value

visibility time

expec. value for # SNe in given galaxy

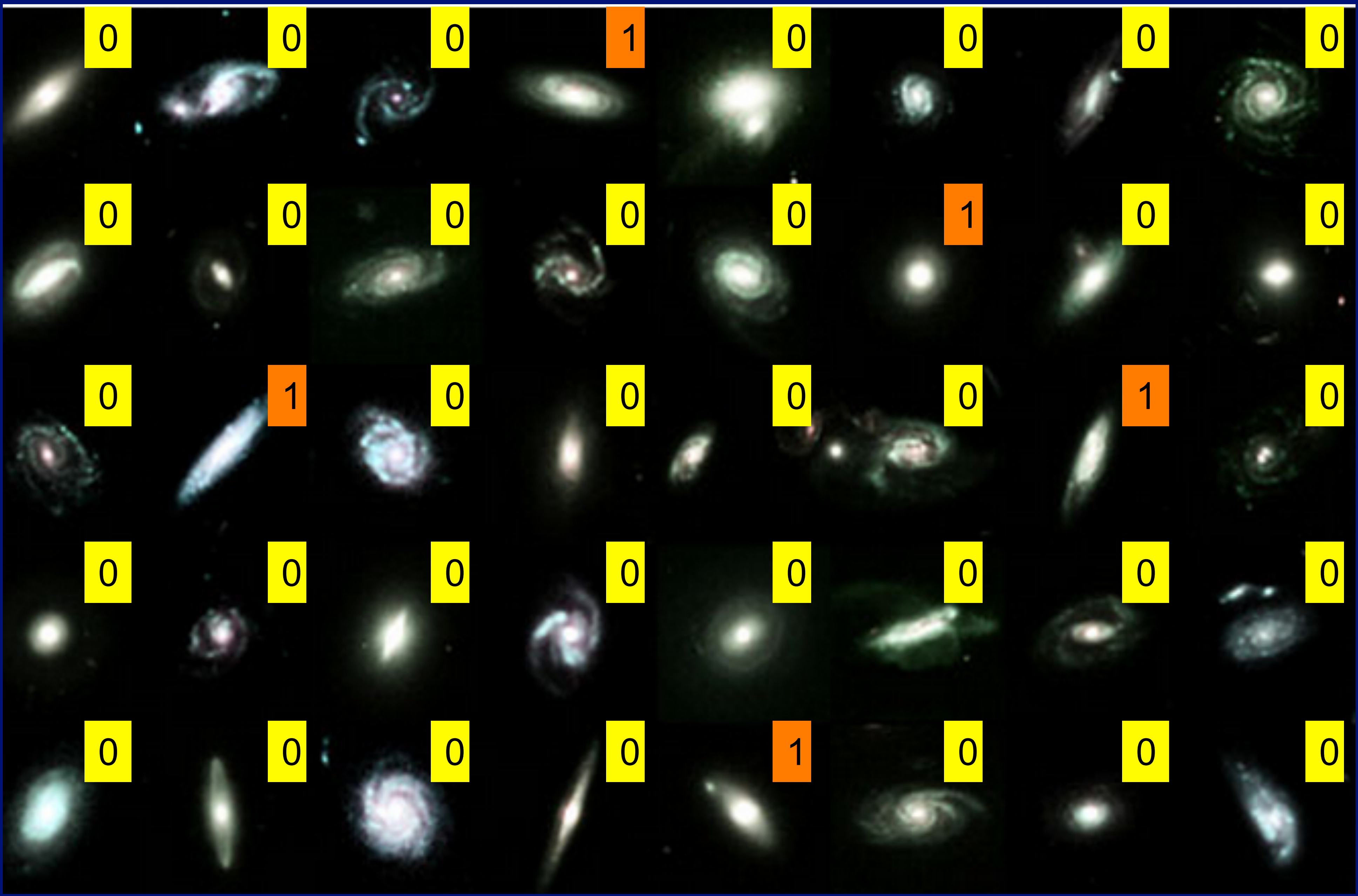
visibility time

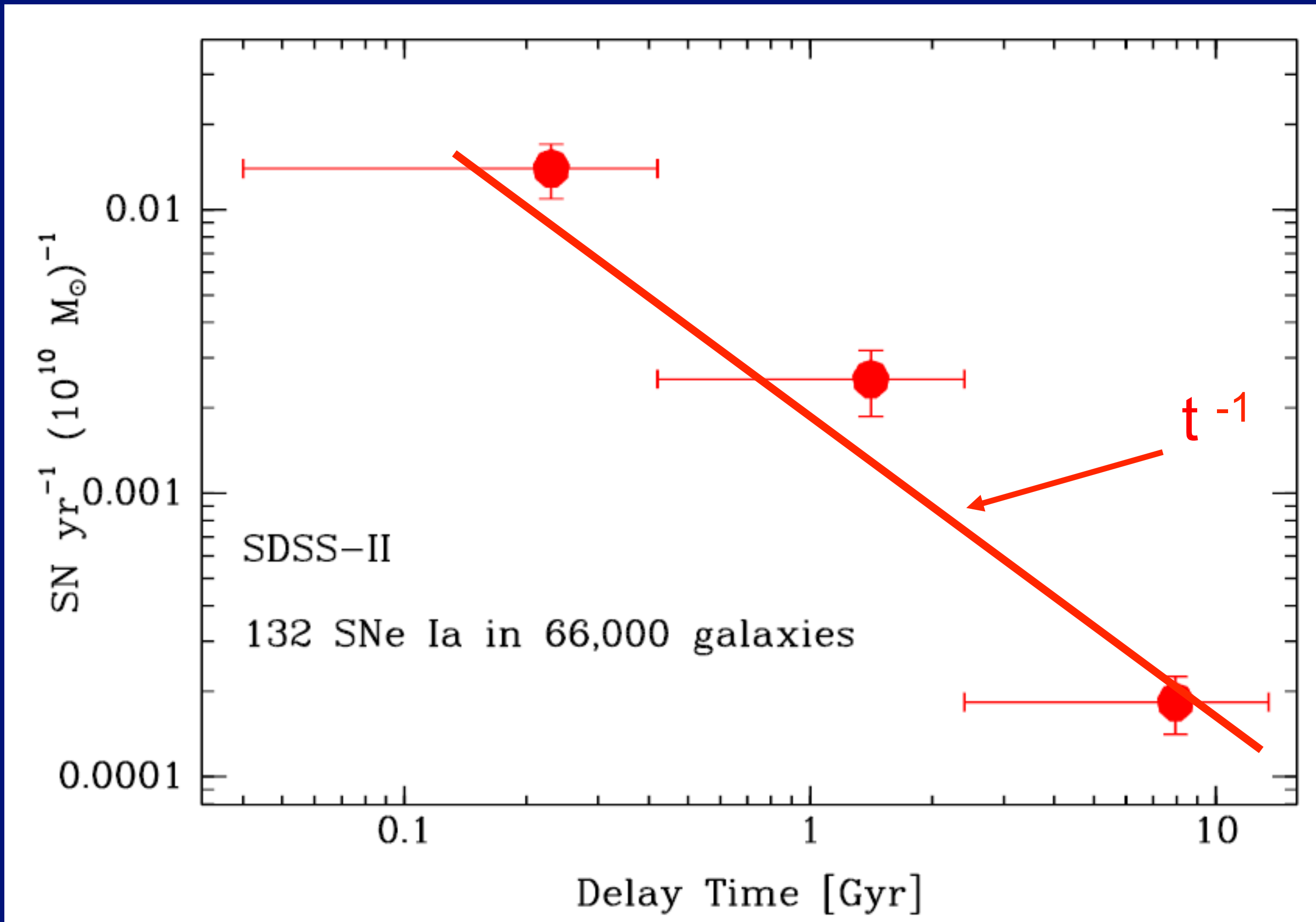
N = r • t

$$\lambda_i = r_i t_i,$$

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

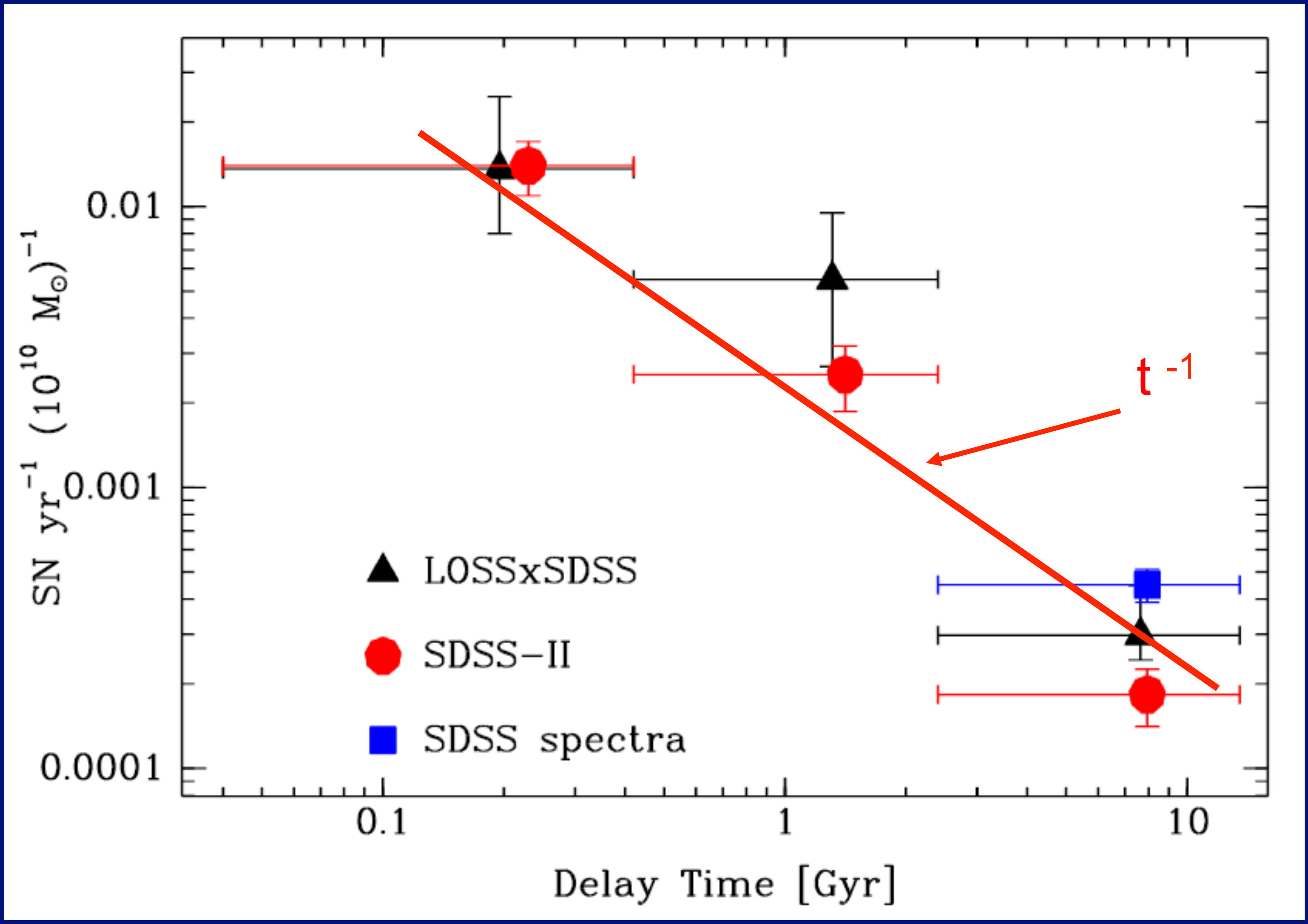
Compare observed number of SNe (0 or 1) in each galaxy to expectation value for given model DTD





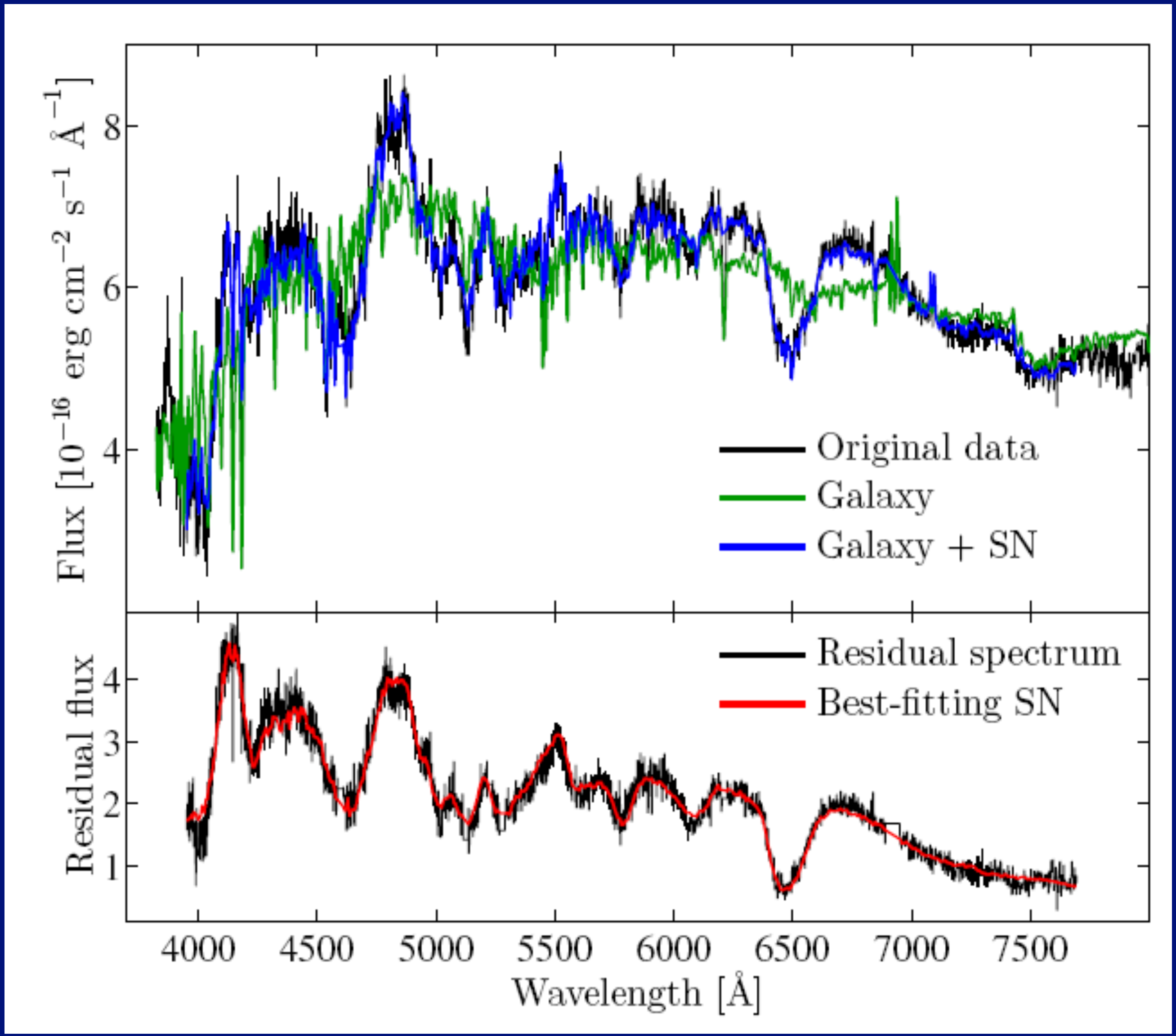
Maoz, Brandt, Mannucci 2012

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



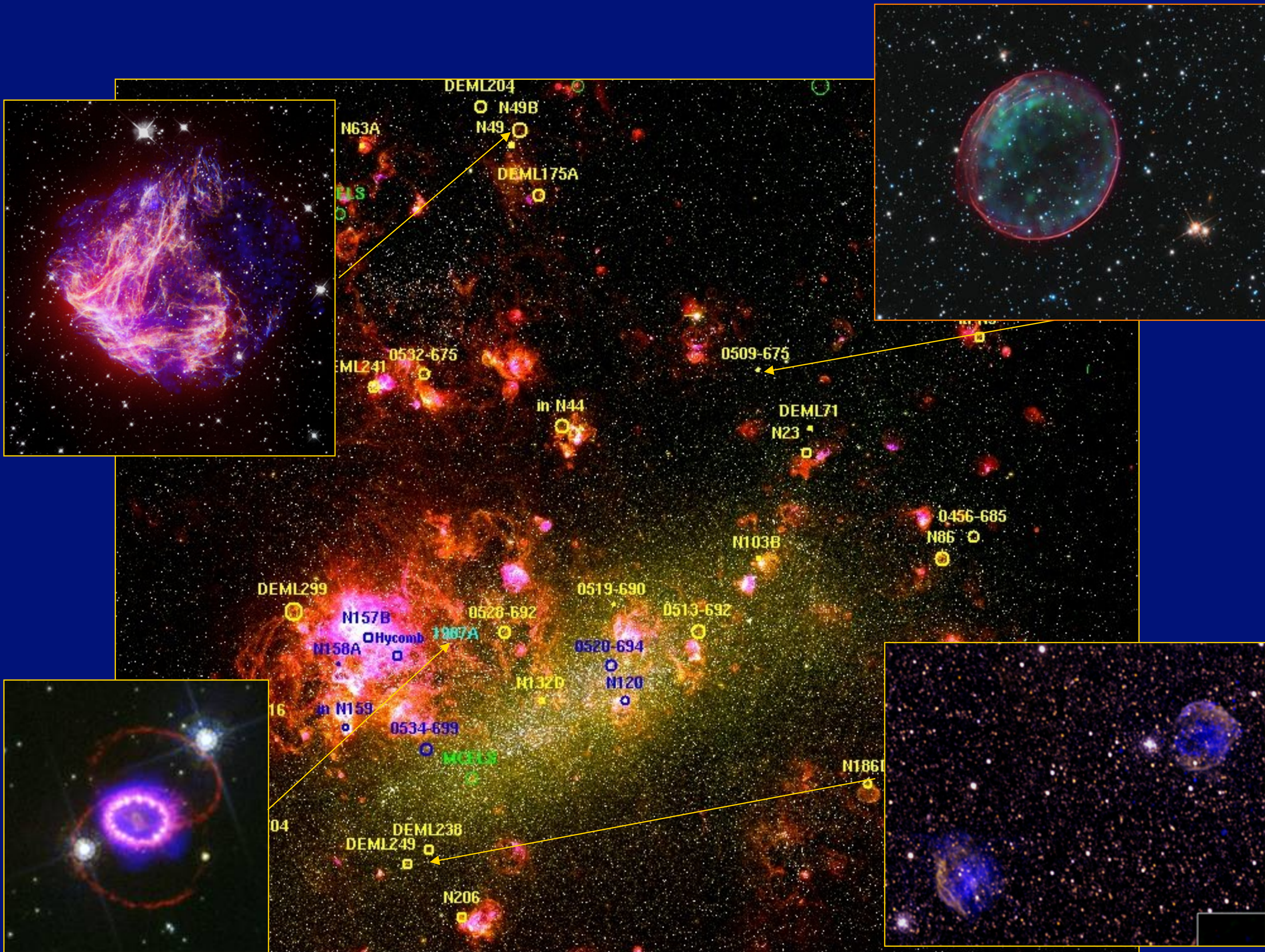
Maoz+11, Maoz+12, Graur & Maoz 12

A SN survey among 700,000 SDSS spectra: 90 SNe Ia (Graur & Maoz 12)



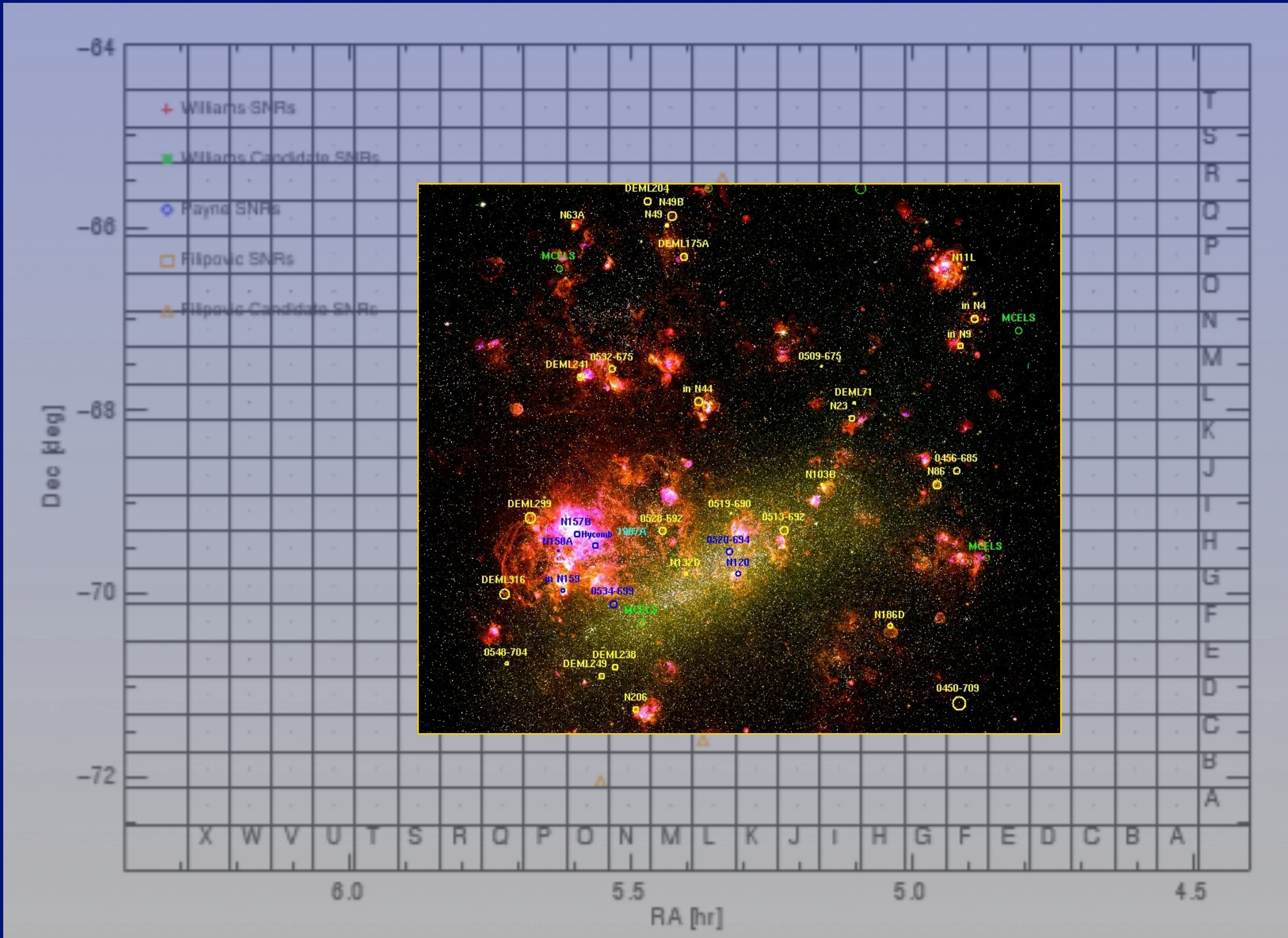
How to recover the delay time distribution

or even…SN remnants in the LMC+SMC, viewed as a SN survey



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

Stellar age distributions in 1836 individual LMC/SMC "cells", from resolved stellar populations.
Harris & Zaritzky 2004, 2009



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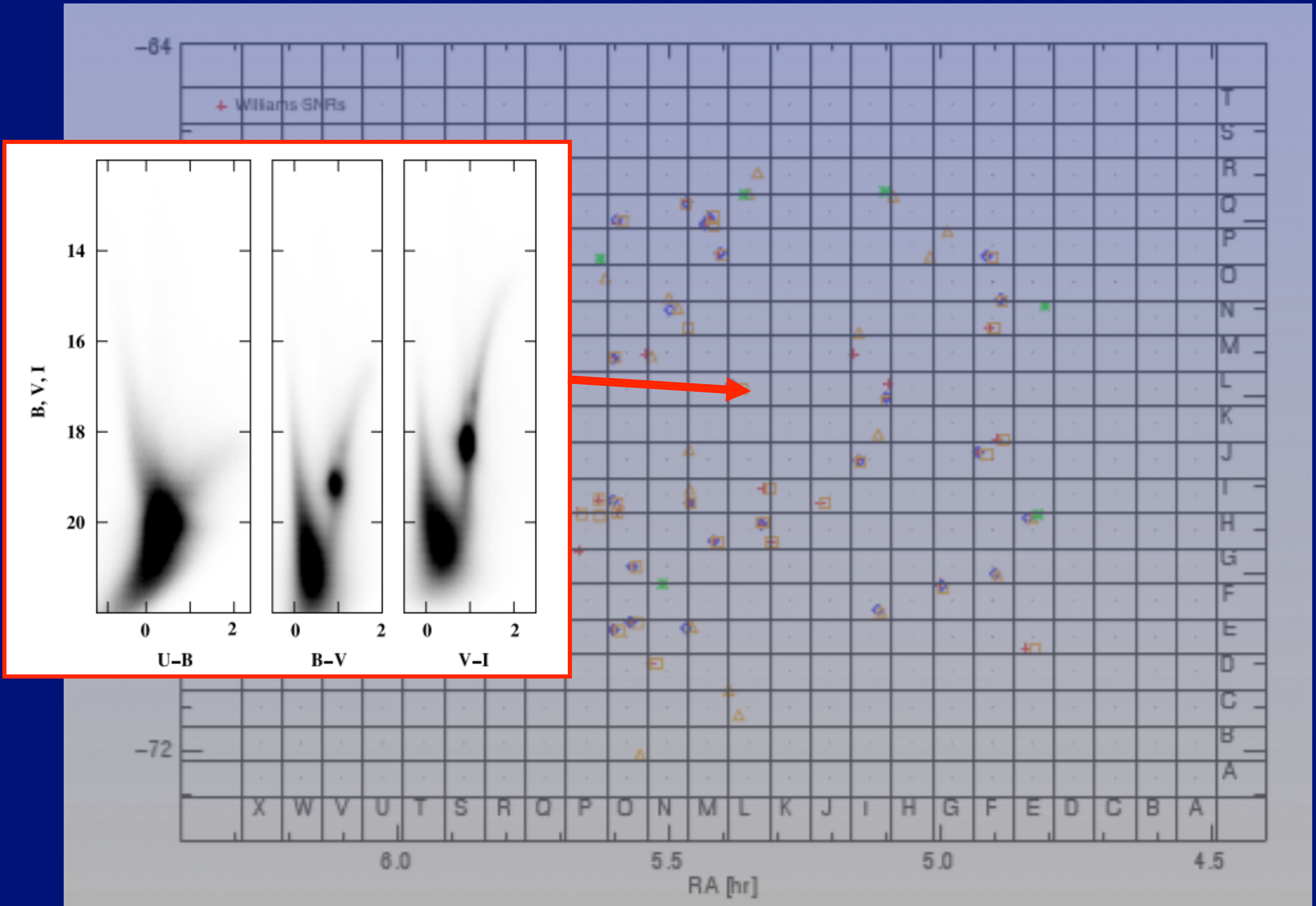

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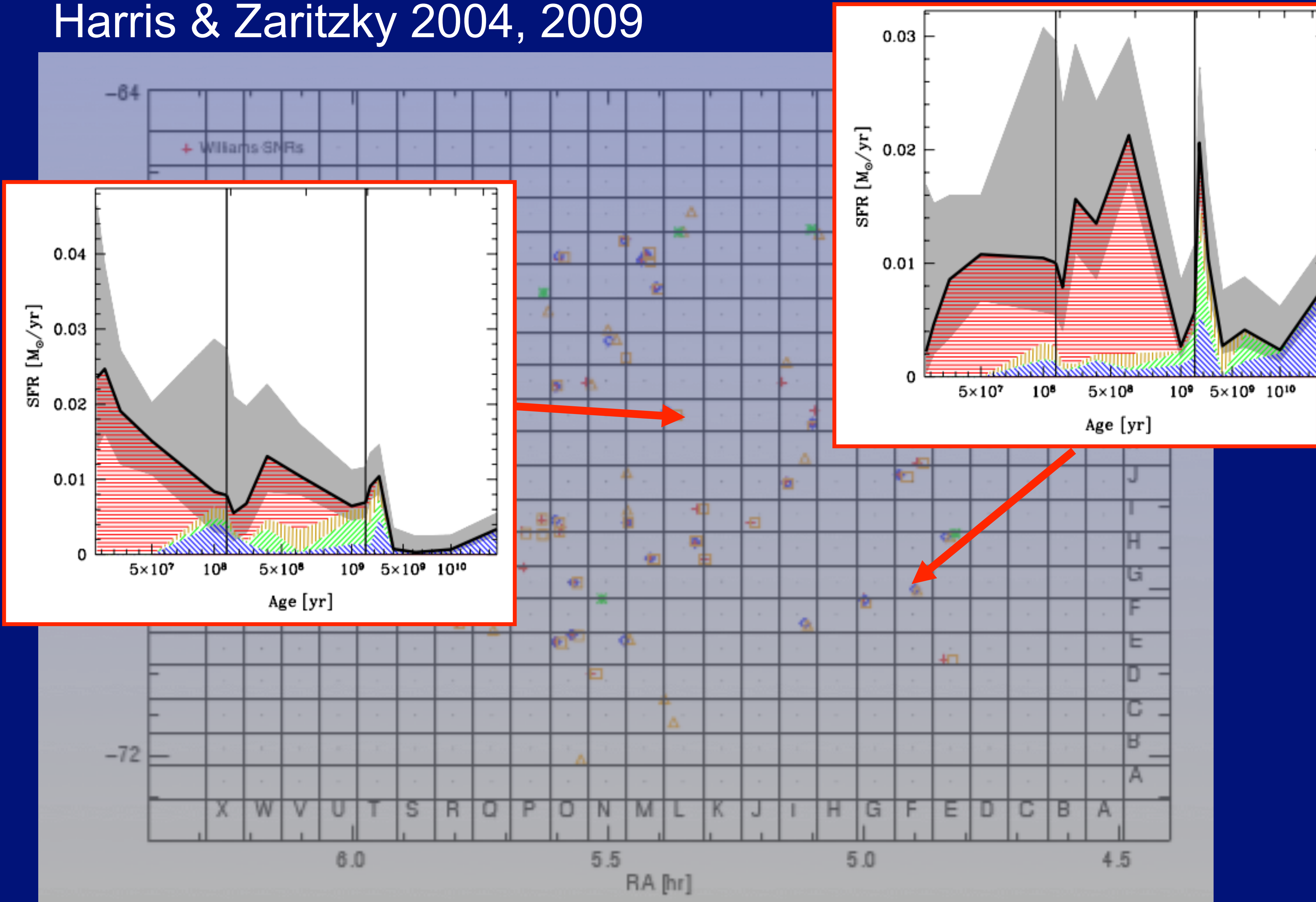
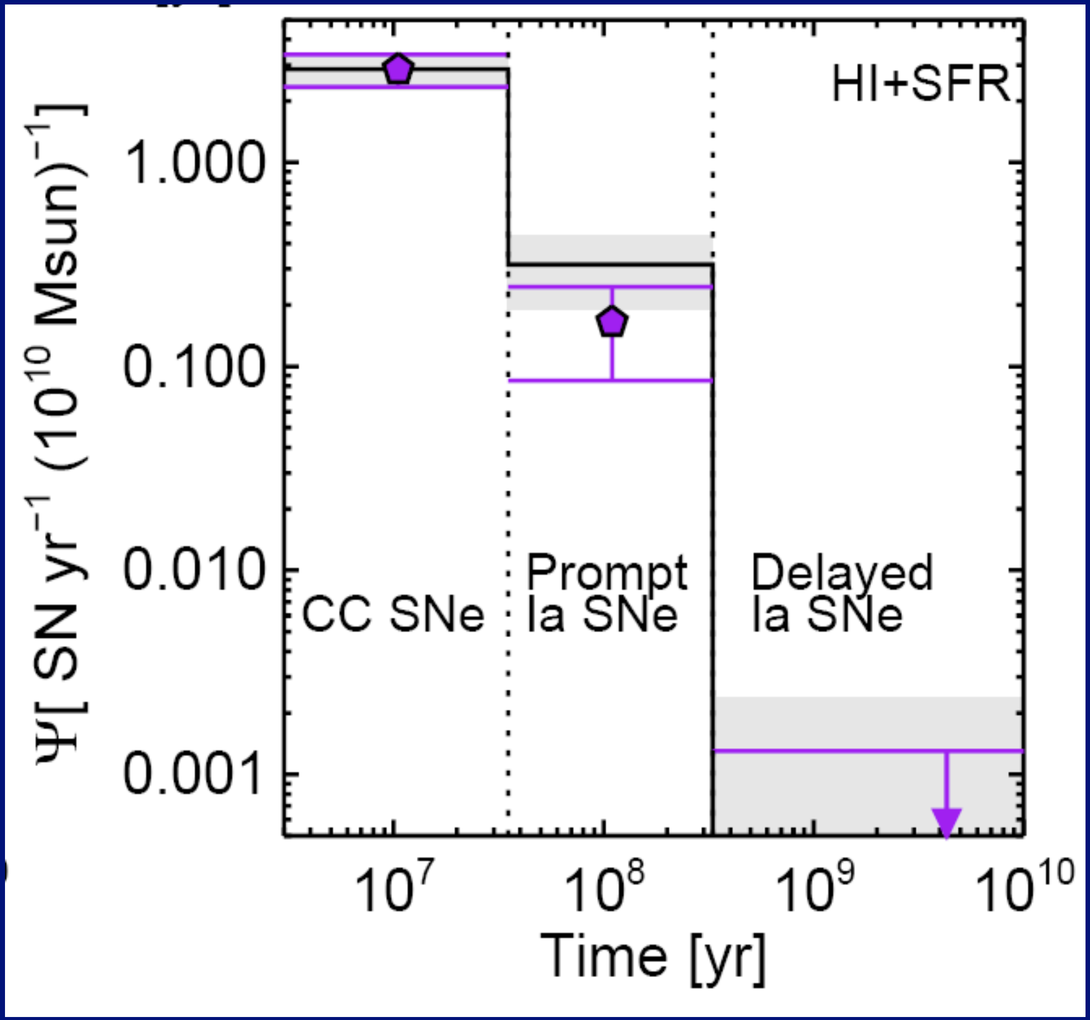


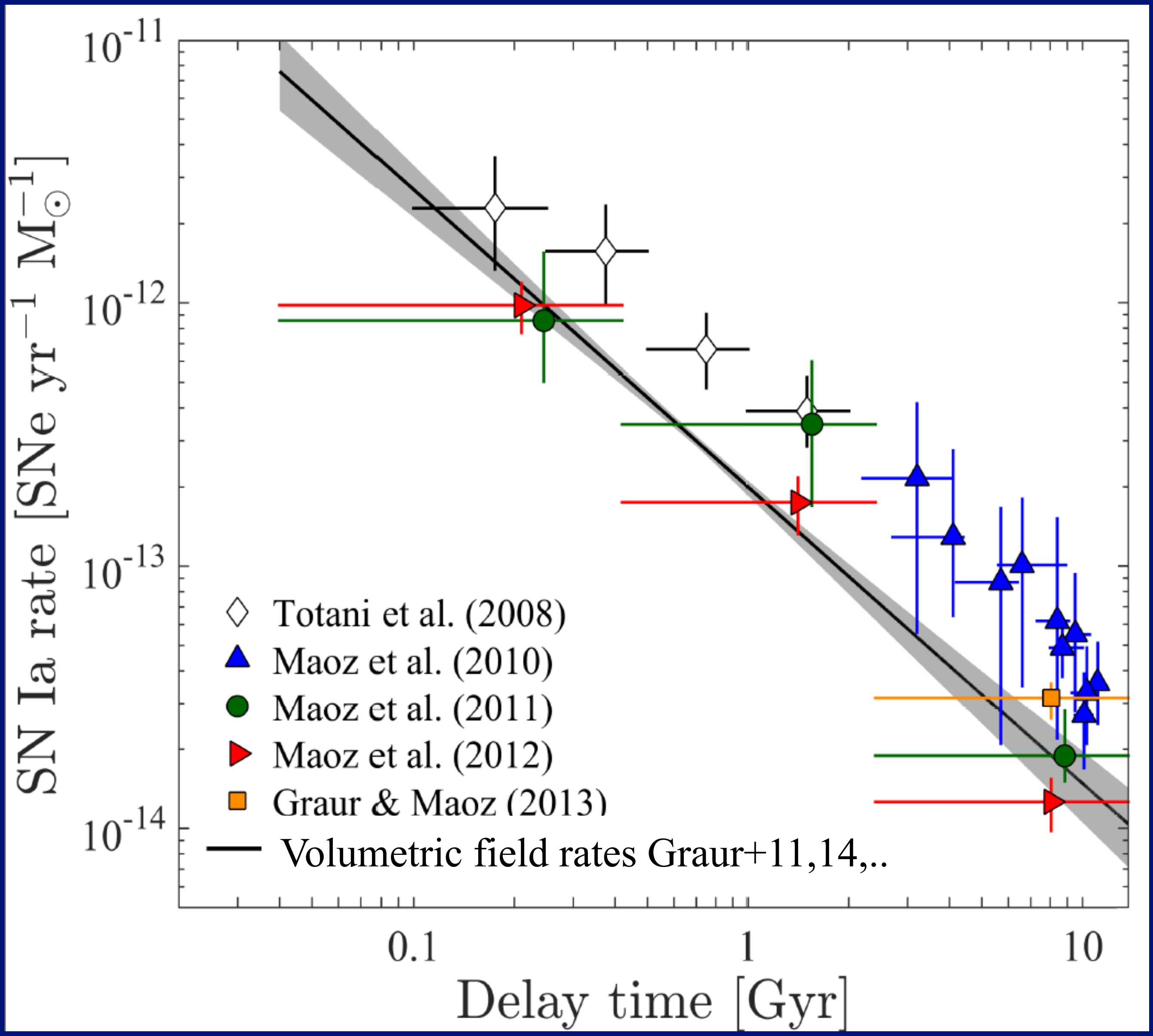


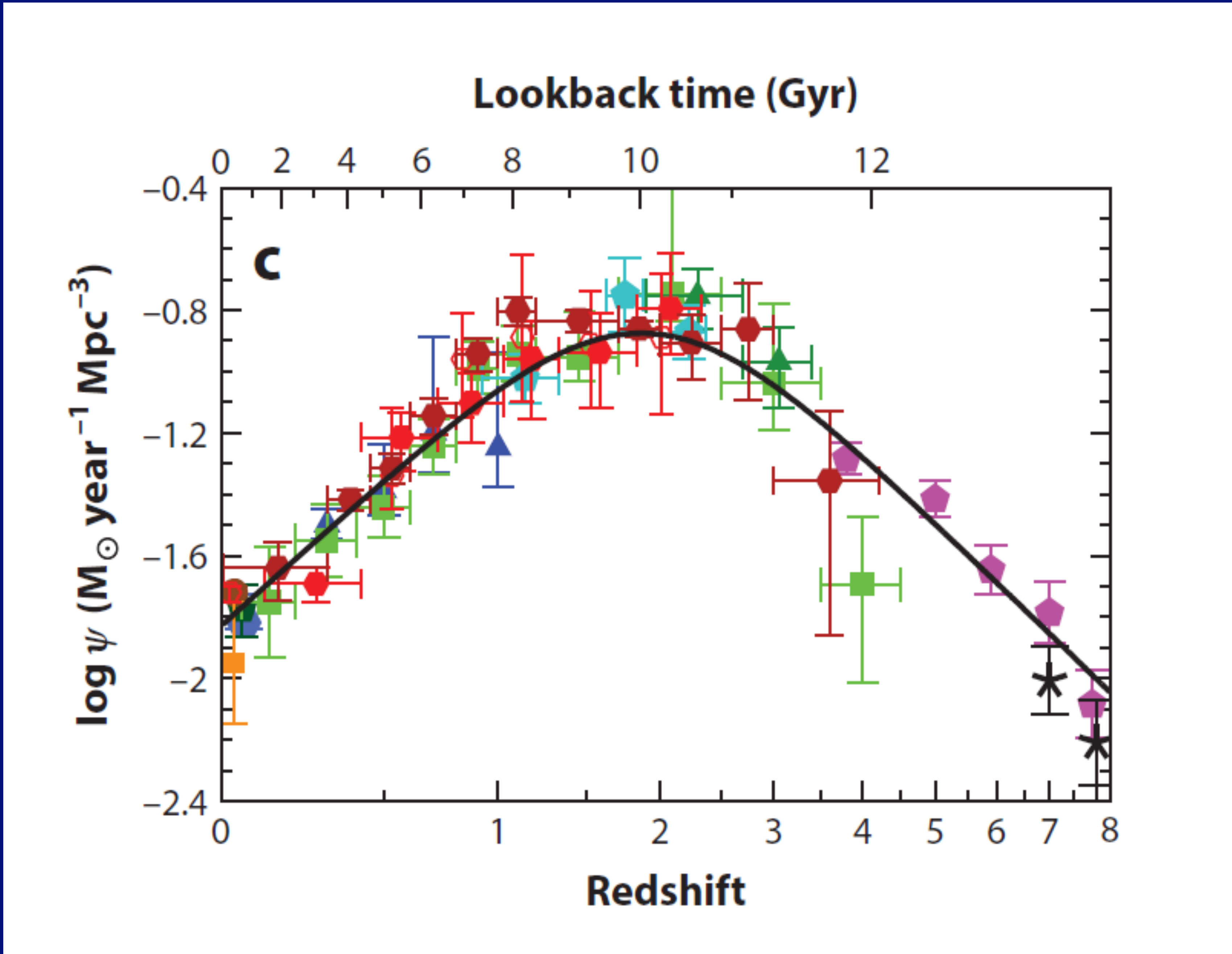
Maoz & Badenes 2010

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

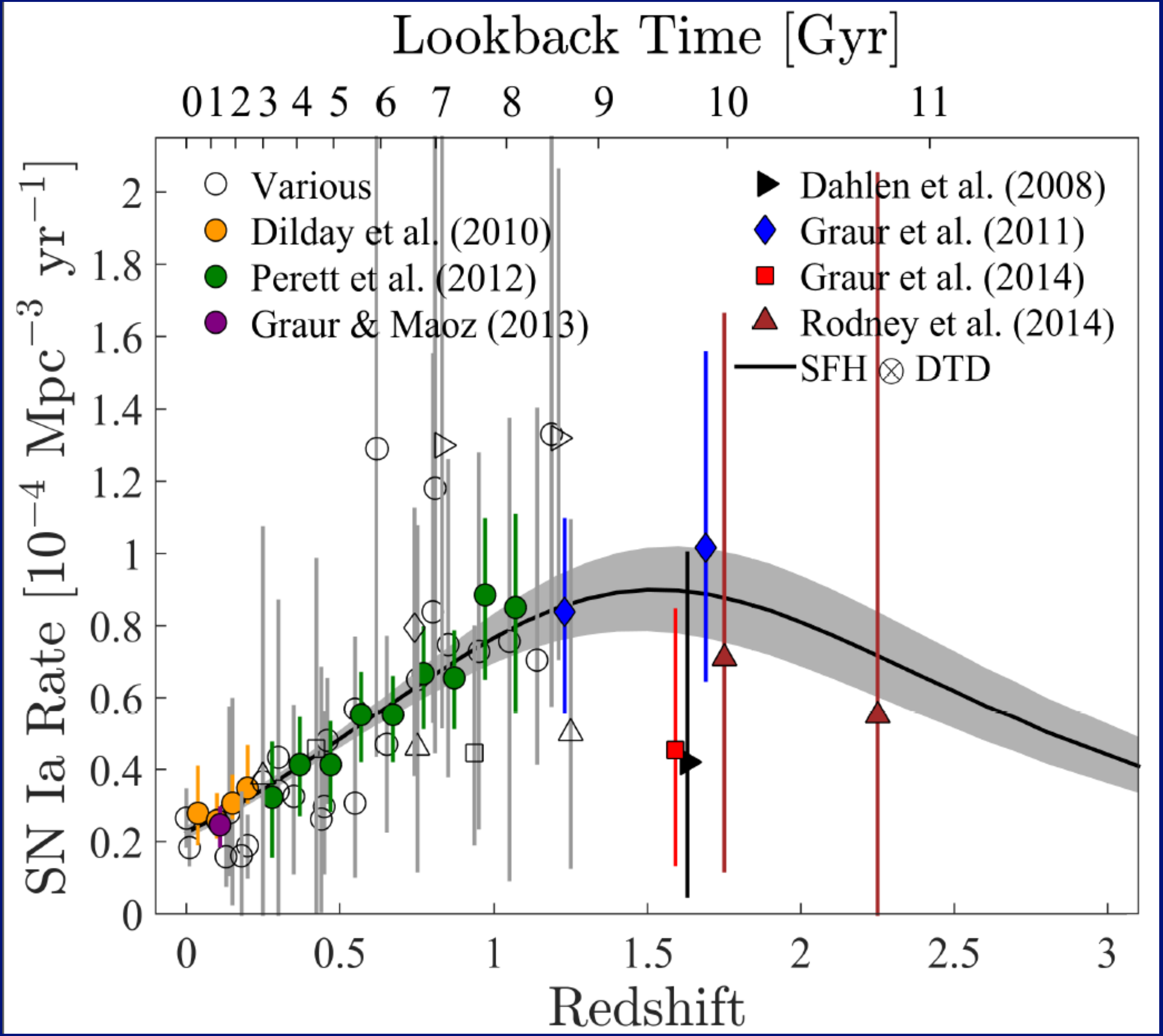
A consistent picture:

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





Madau & Dickinson 14



Lookback Time [Gyr]
0 1 2 3 4 5 6 7 8 9 10 11
SN Ia Rate [10^{-4} Mpc^{-3} yr^{-1}]
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
Various
Dilday et al. (2010)
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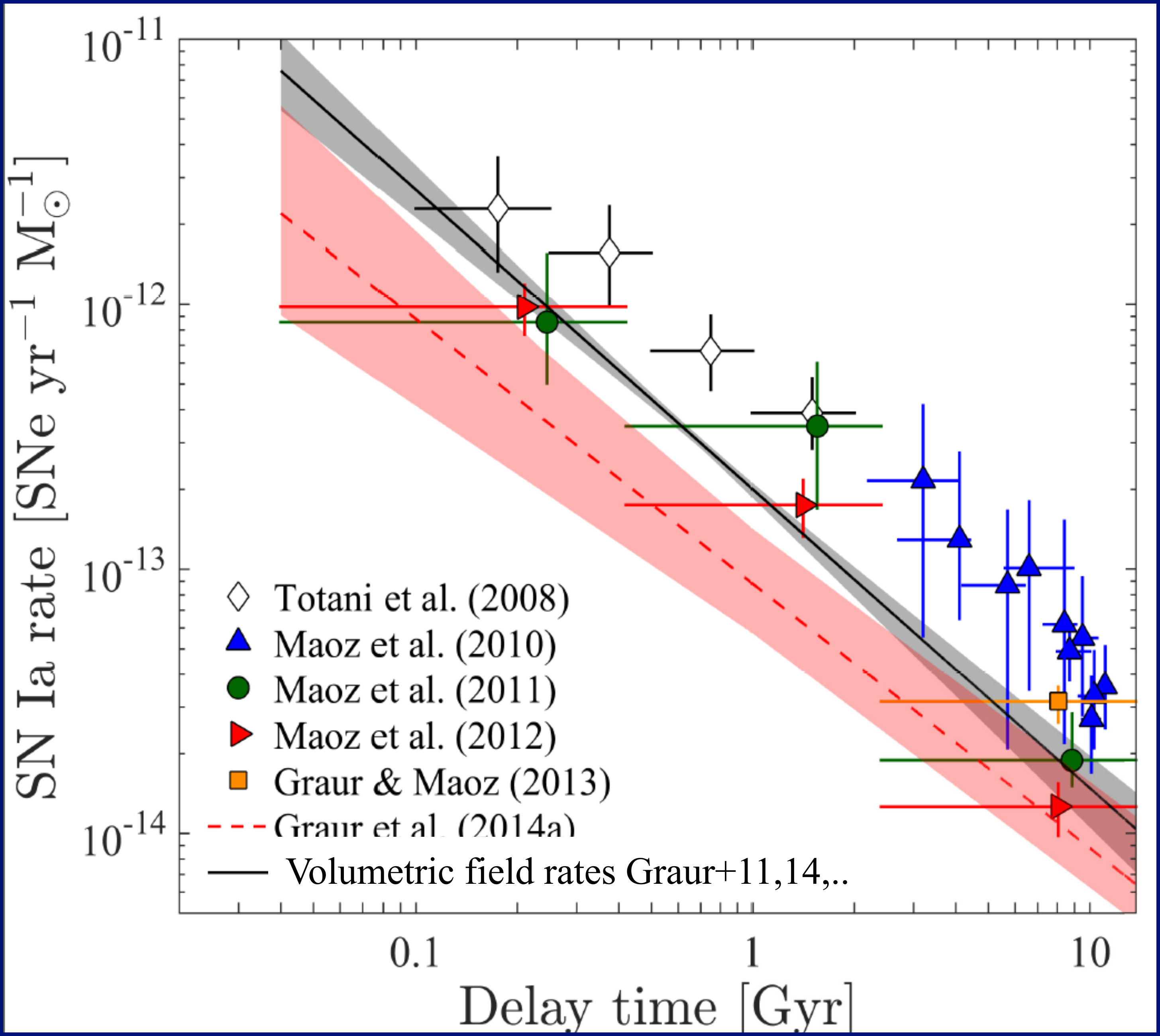
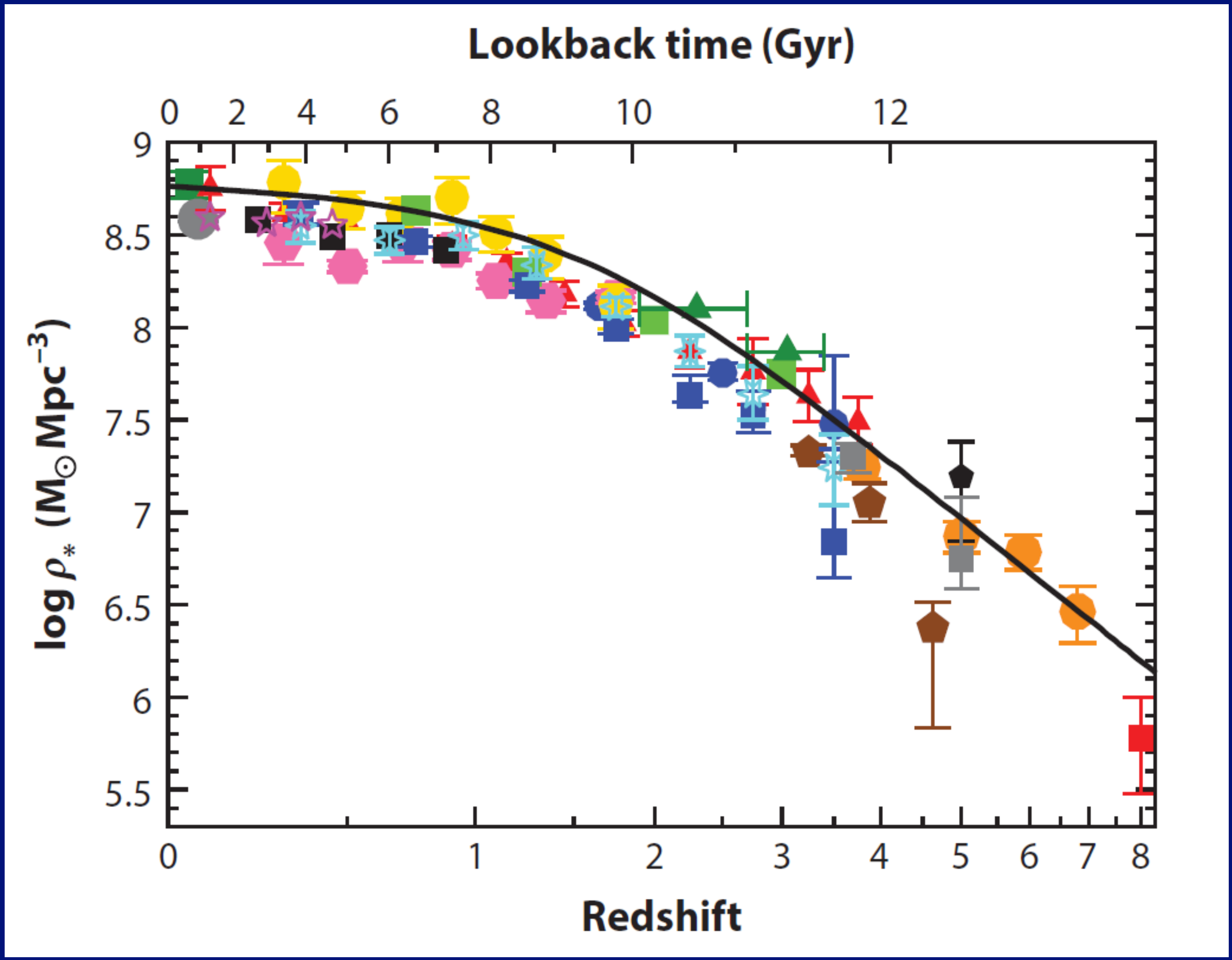
Redshift



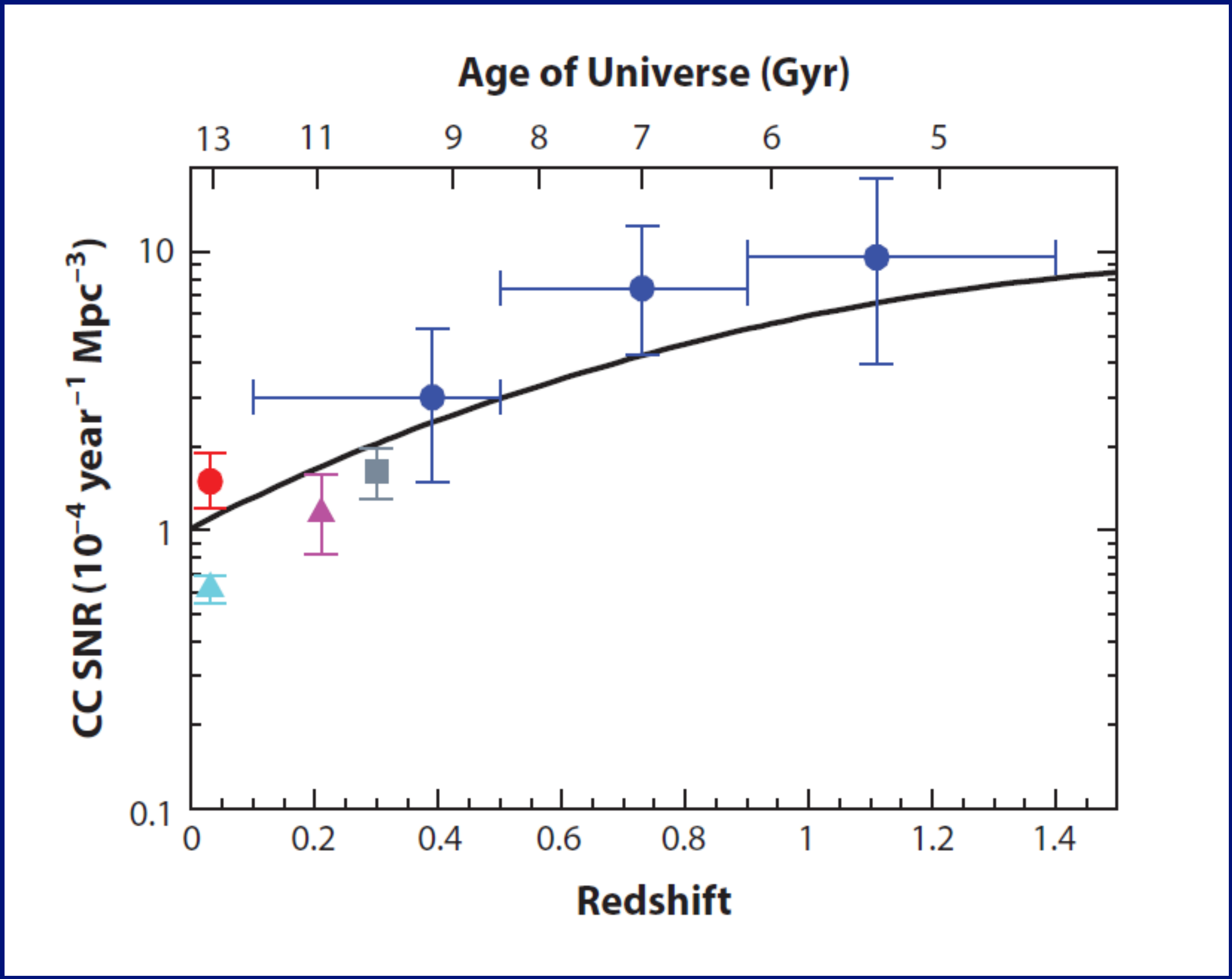
SN Ia rate [SNe yr^{-1} M$_\odot^{-1}$]
Delay time [Gyr]
10^{-11}
10^{-12}
10^{-13}
10^{-14}
0.1
1
10
Totani et al. (2008)
Maoz et al. (2010)
Maoz et al. (2011)
Maoz et al. (2012)
Graur & Maoz (2013)
Graur et al. (2014a)
Volumetric field rates Graur+11,14,..

Time-integrated SFR now matches stellar density vs. z



Core-collapse SNe: "instantaneous" after star formation → CC SN rate must track the cosmic SFR. For standard IMF: 0.01 SNe per formed Msun.

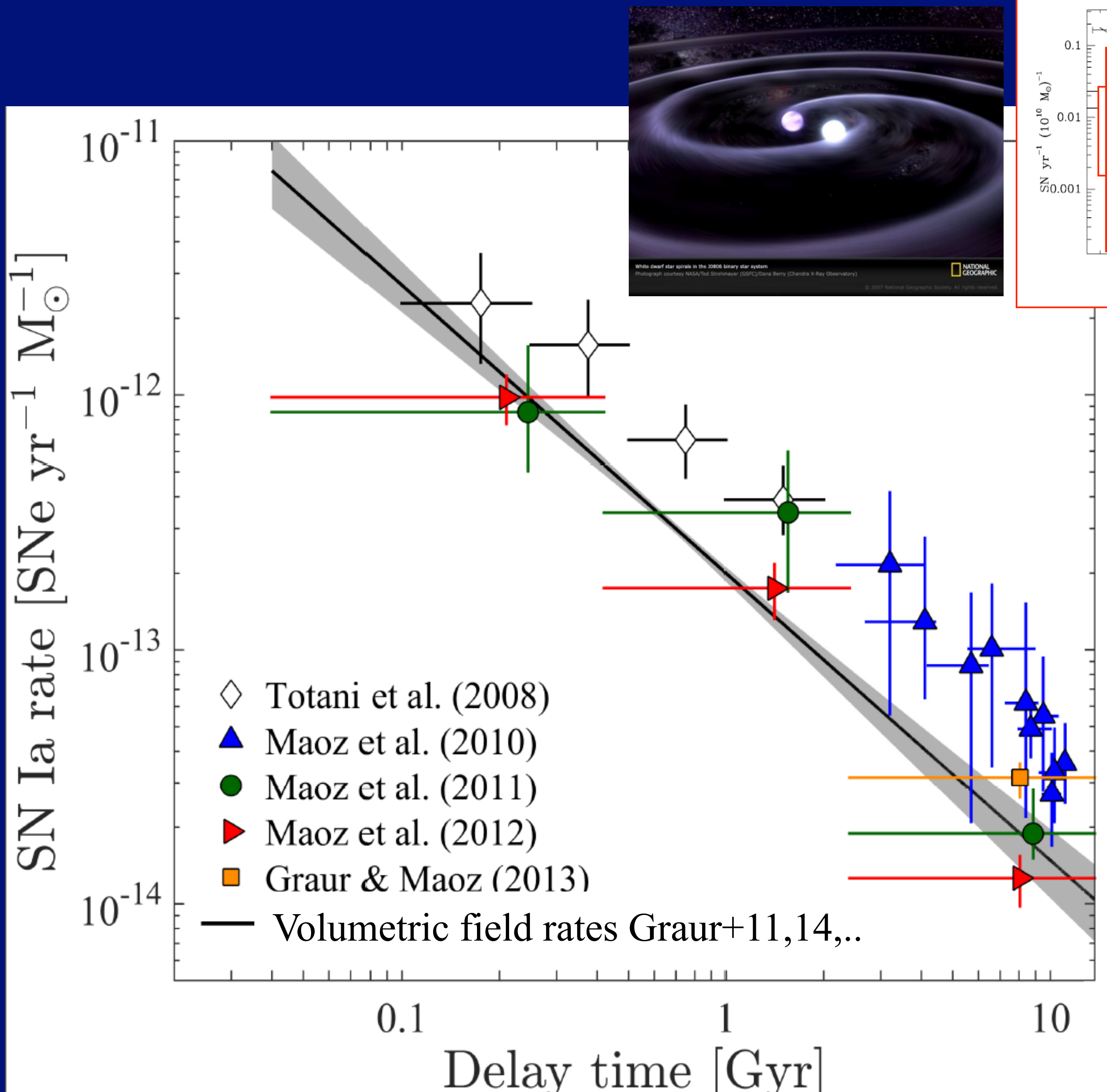
Expected CC rate vs. z now matches observations

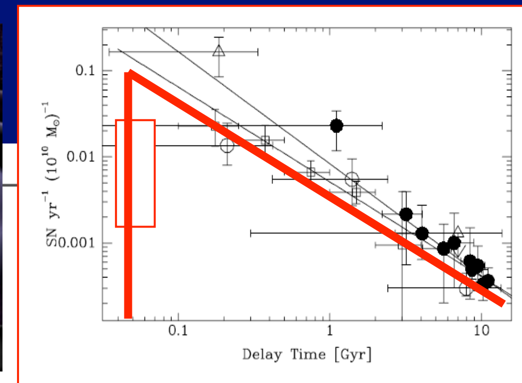


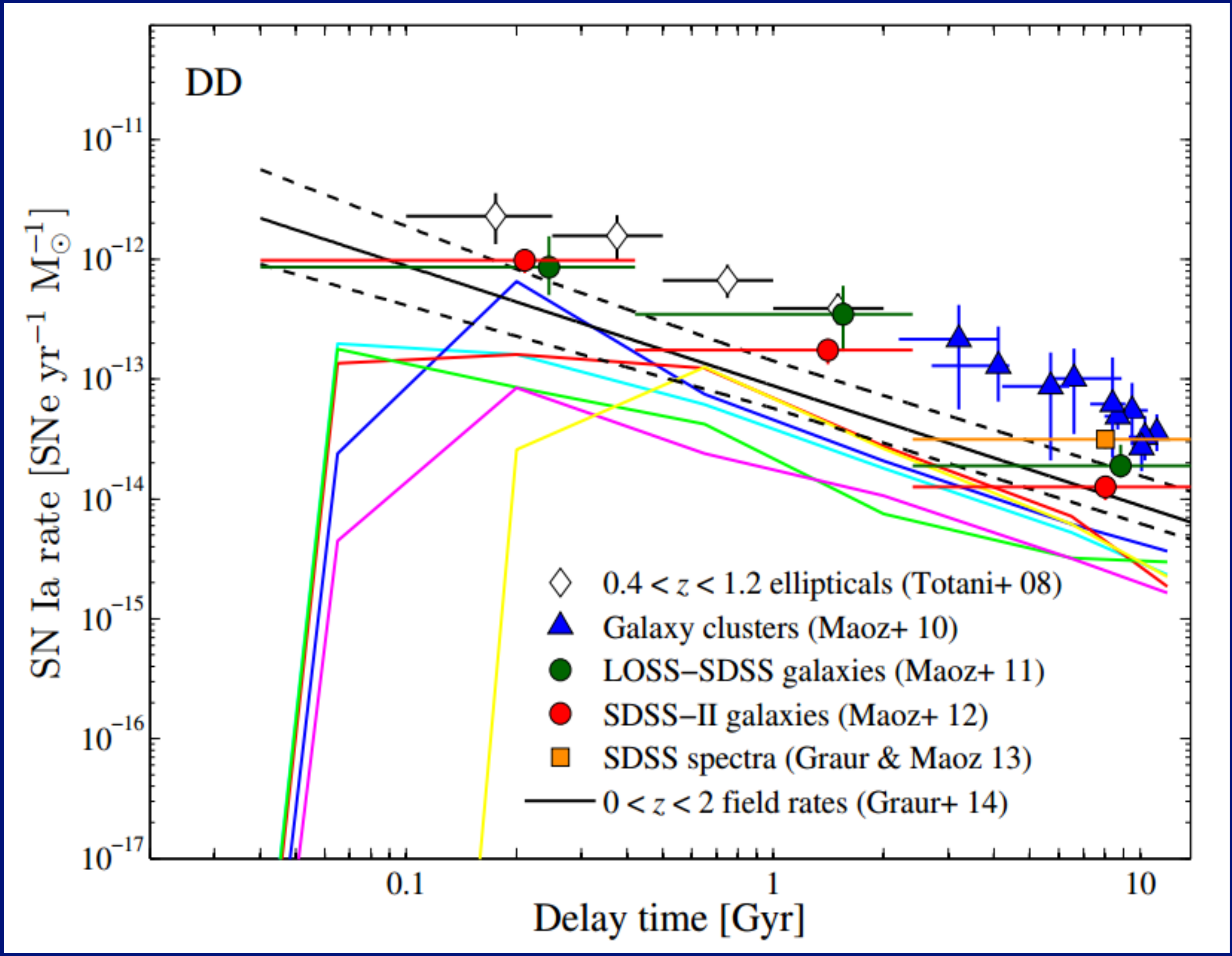
Madau & Dickinson 14

A consistent picture:

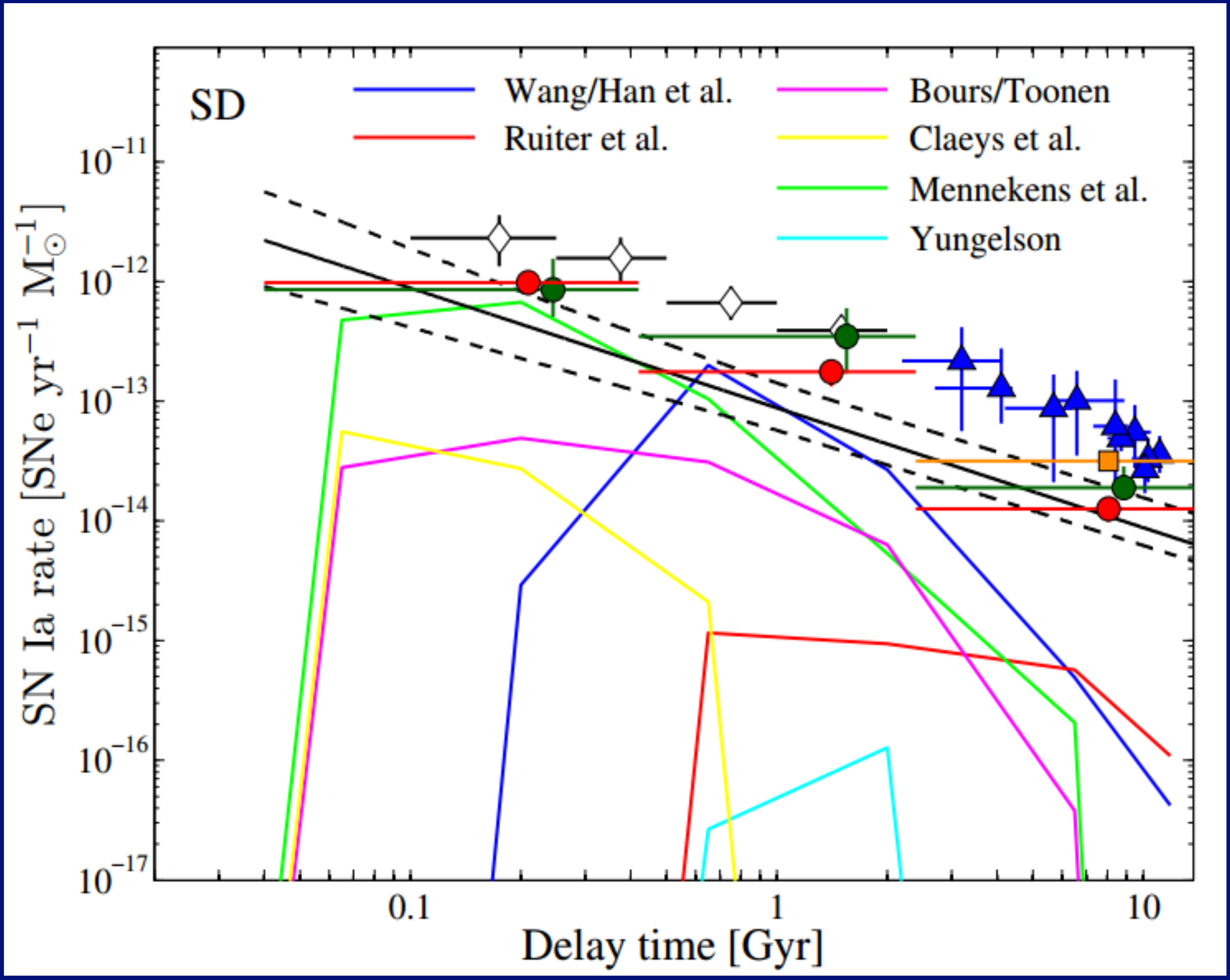
* Wide distribution of delay times, looks like ~ t^{-1} (DD?)







DD
SN Ia rate [SNe yr^{-1} M$_\odot^{-1}$]
Delay time [Gyr]
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
0.1
1
10
0.4 < z < 1.2 ellipticals (Totani+ 08)
Galaxy clusters (Maoz+ 10)
LOSS−SDSS galaxies (Maoz+ 11)
SDSS−II galaxies (Maoz+ 12)
SDSS spectra (Graur & Maoz 13)
0 < z < 2 field rates (Graur+ 14)


SD
Wang/Han et al.
Ruiter et al.
Bours/Toonen
Claeys et al.
Mennekens et al.
Yungelson
SN Ia rate [SNe yr^{-1} M$_\odot^{-1}$]
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
0.1
1
10
Delay time [Gyr]

Questions

Can we find a progenitor channel(s) that:

1. makes things that look like normal Ia's

and

2. makes enough of them (while satisfying progenitor population observational constraints)

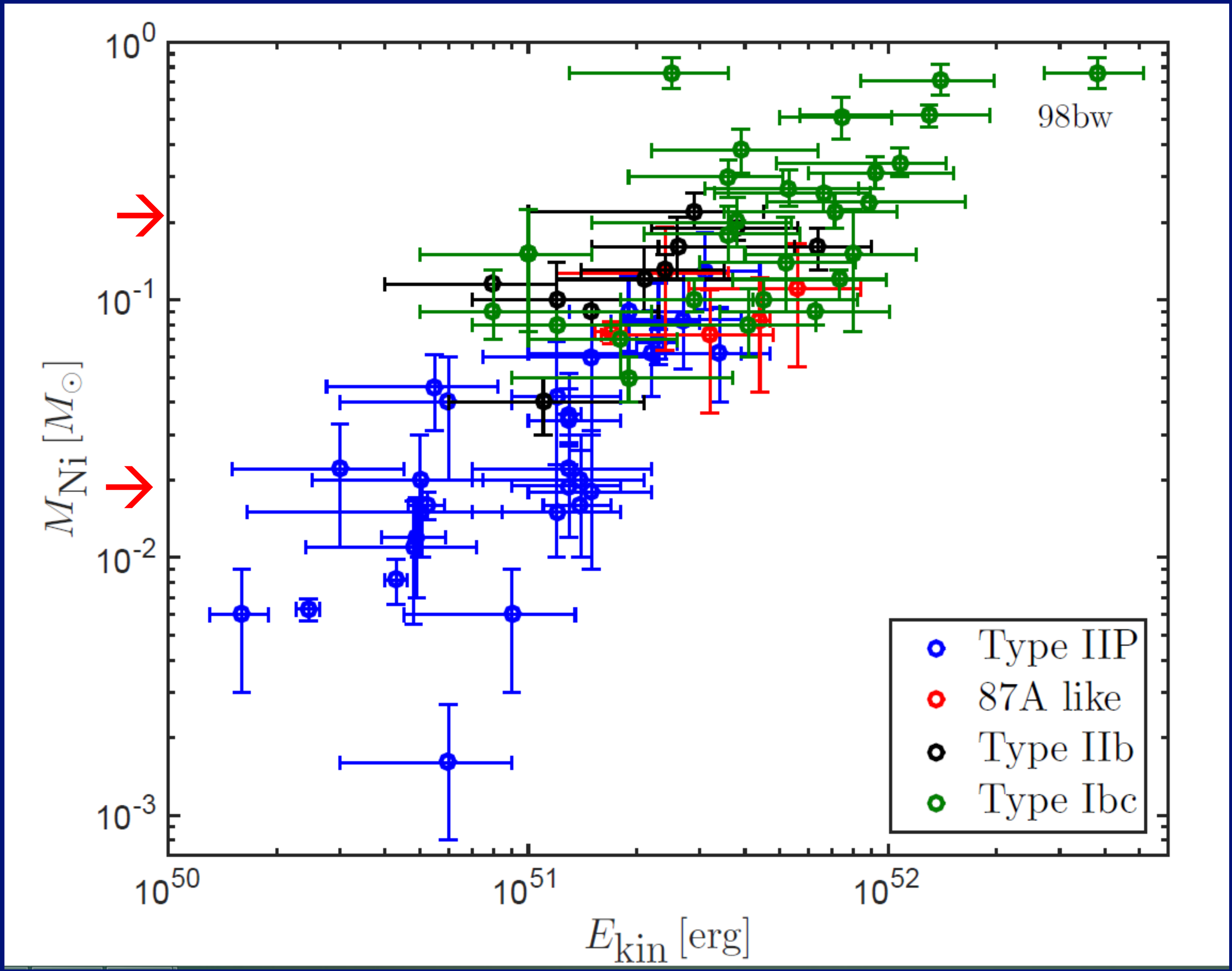
and

3. gives them a 1/t DTD?

CC iron yields are measurable directly from the SN light curves

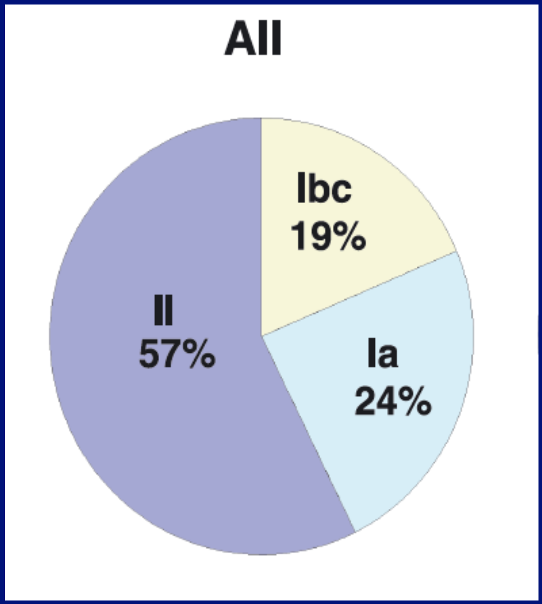
0.2 Msun

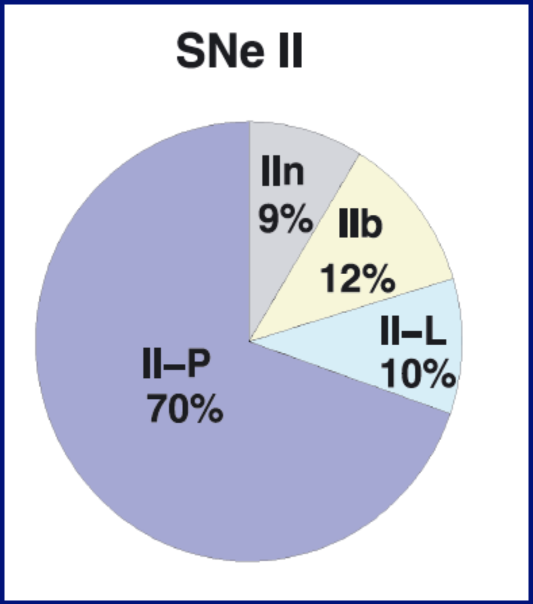
0.02 Msun



Kushnir 15

Ratio of 3:1 Types II to Ibc …. Most Type II are IIP



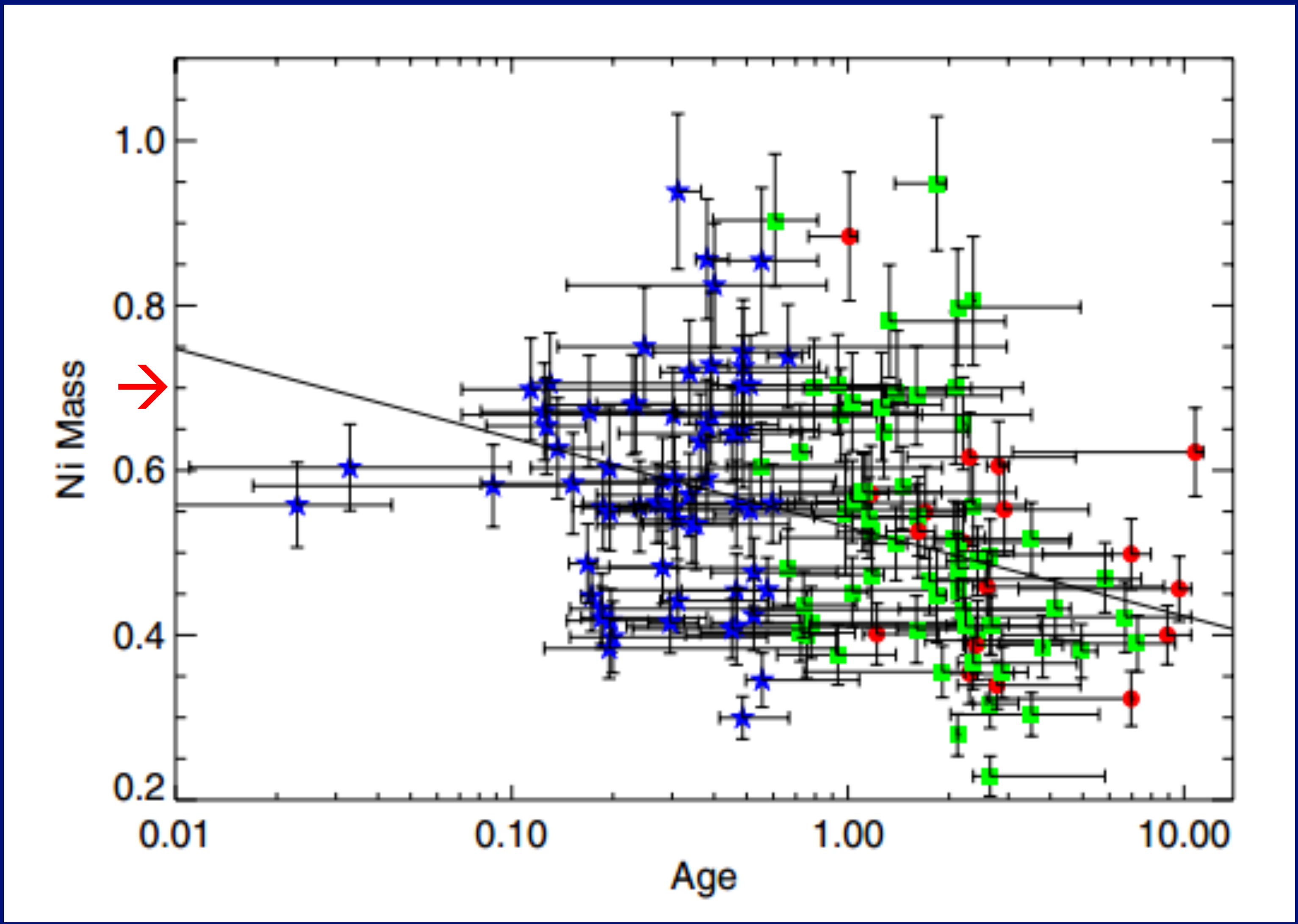


Li+ 2011

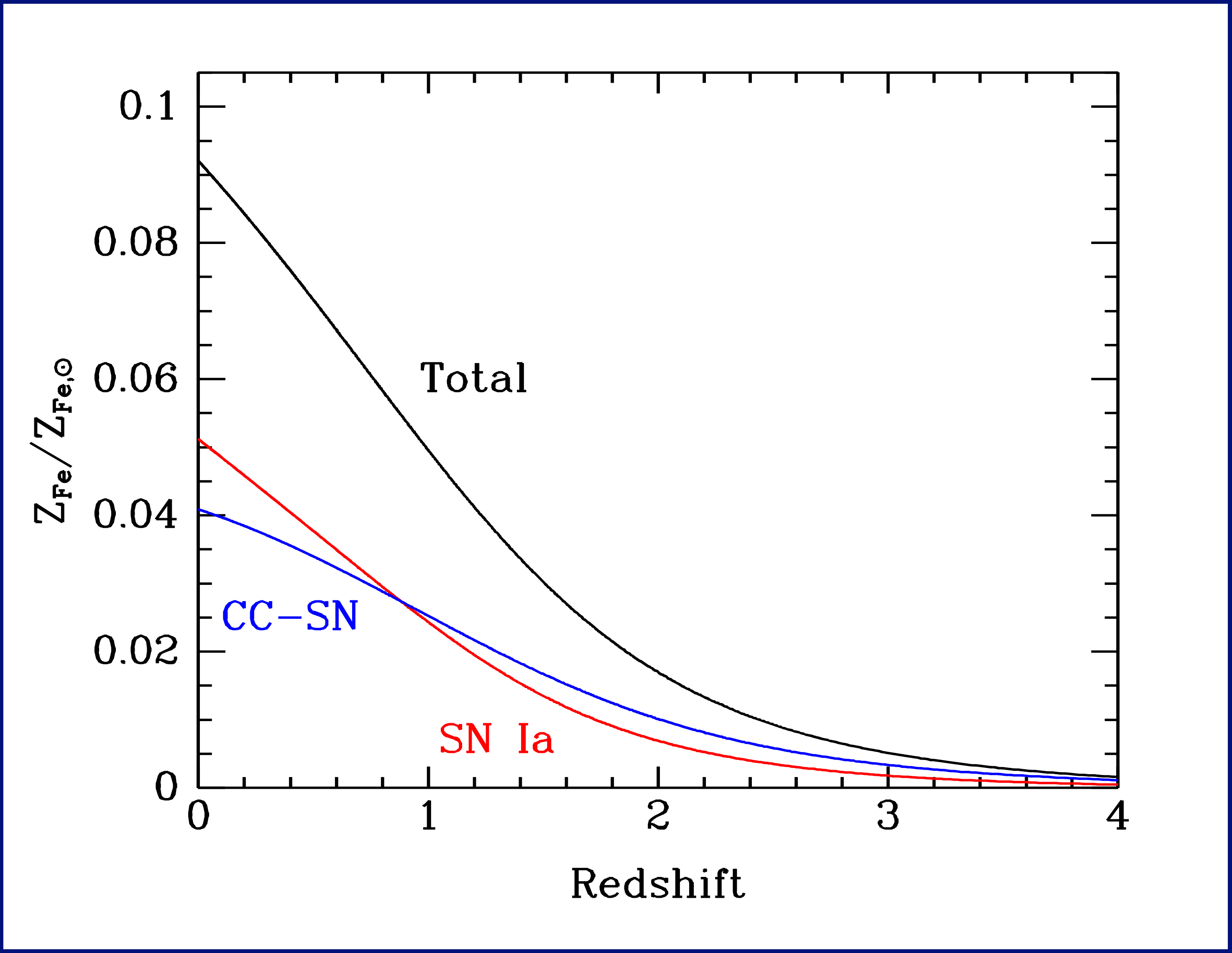
Mean iron yield pr CC SN = ¾ * 0.02 + ¼ * 0.2 = 0.065 Msun

Howell+09

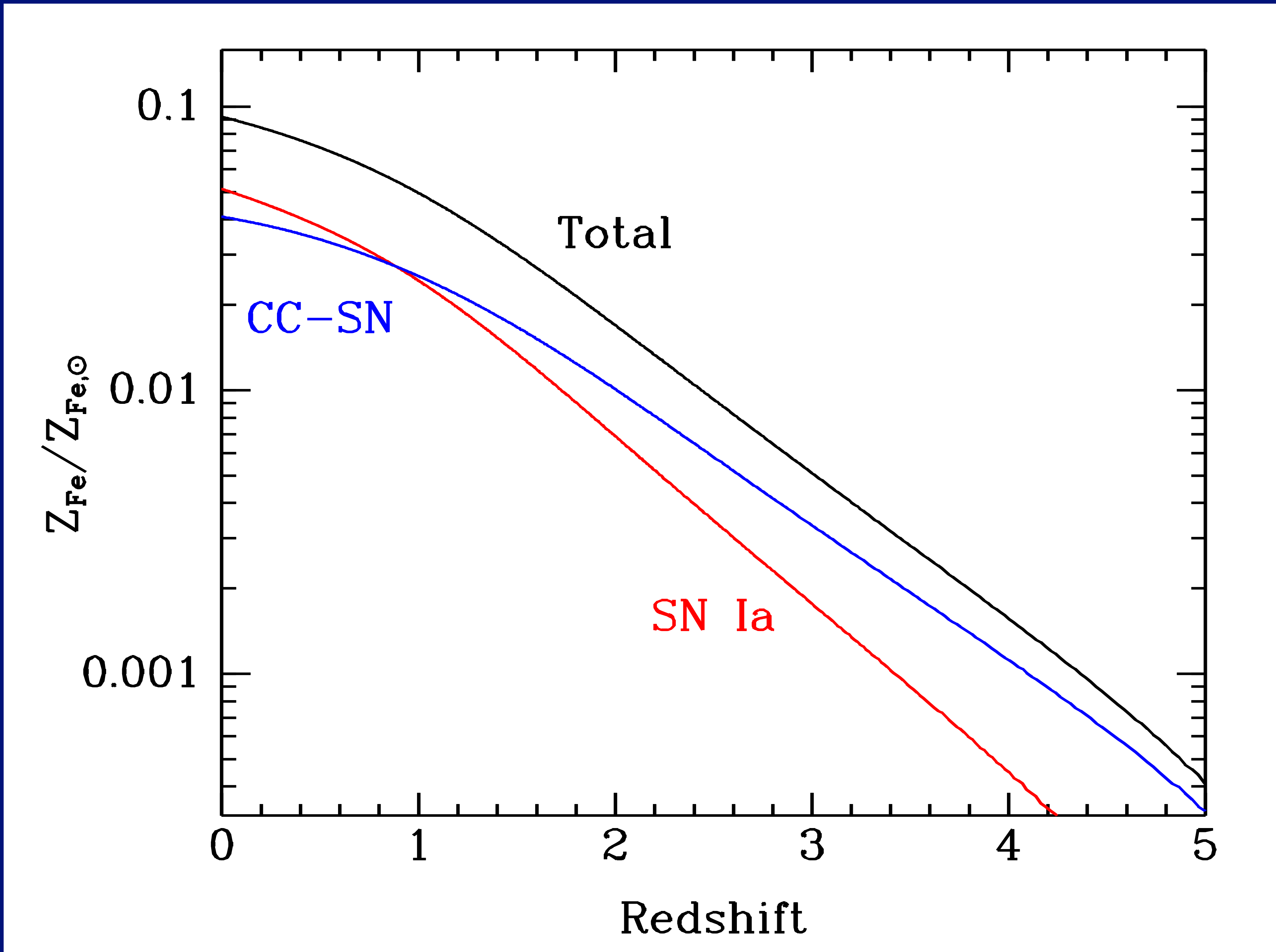
0.7 Msun



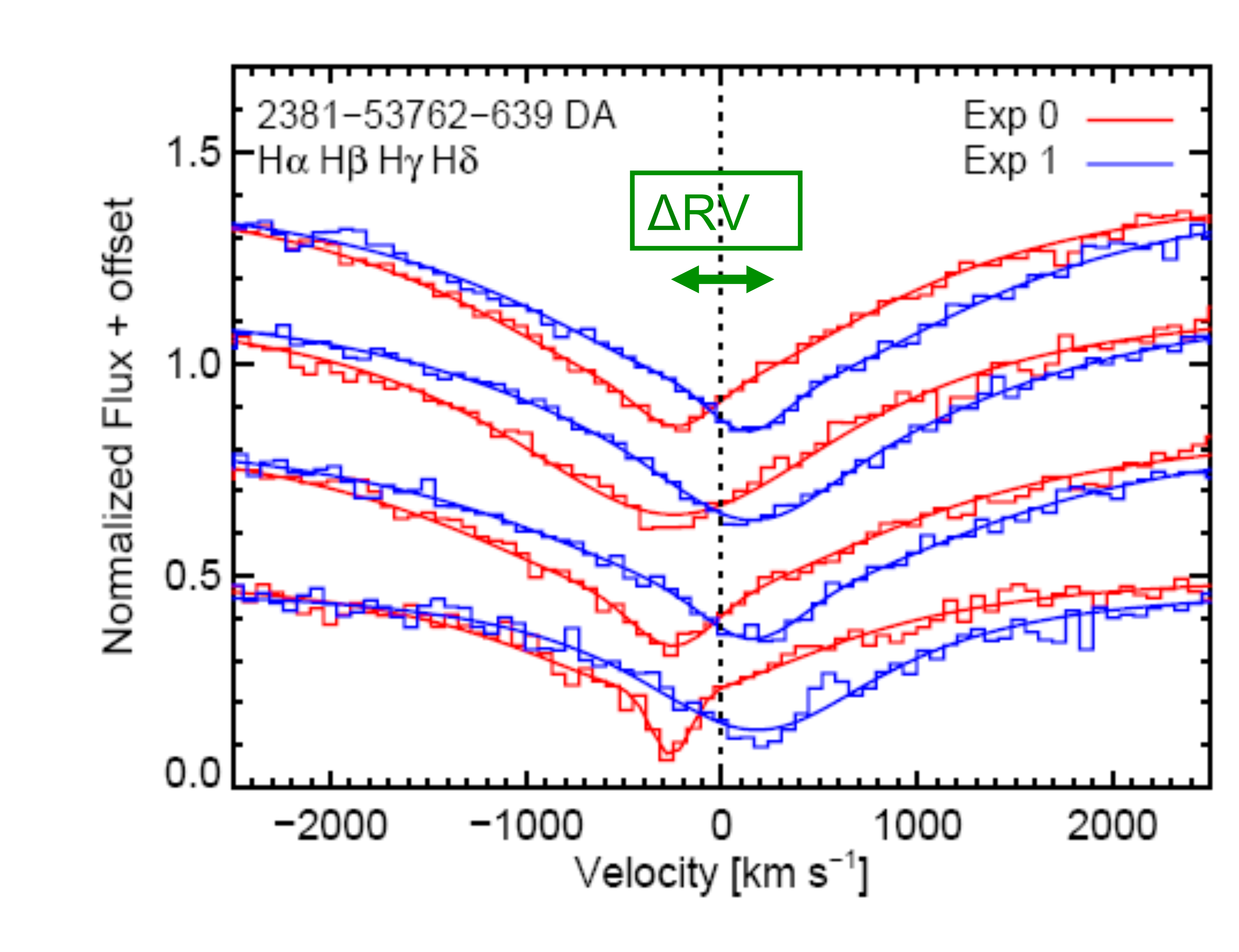
Cosmic iron accumulation history



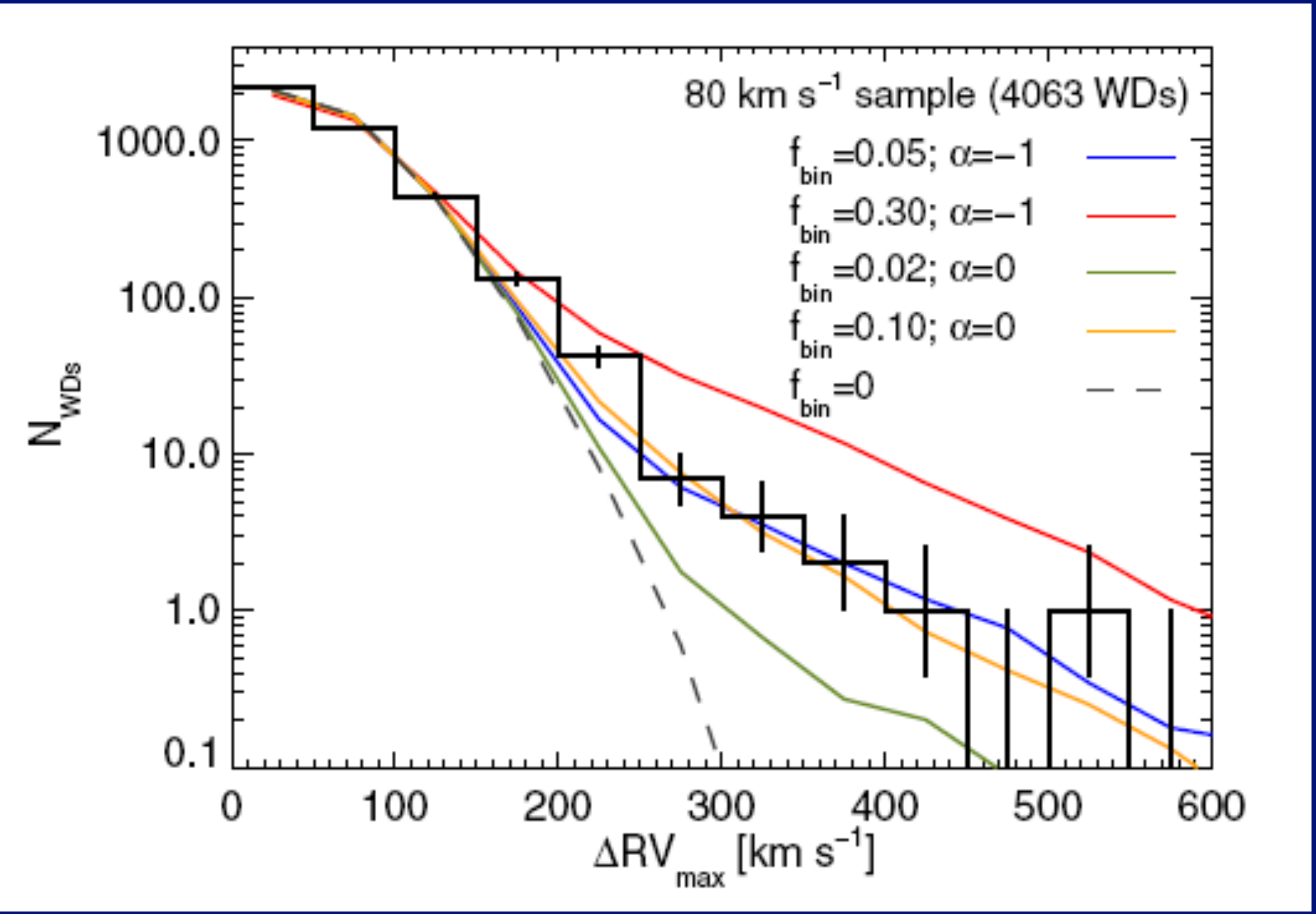
Cosmic iron accumulation history



all SDSS spectra, incl. ~10,000 WDs, have spectra from multiple (2-3) epochs



Observed RV distribution discriminates among models:



Maoz et al. (2012), Badenes & Maoz (2012):

Best-fit model for binary parameter distribution implies total WD merger rate ~ 1×10^{-13} yr^{-1} M^{1}

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

The bivariate distribution of SN delay and explosion energy:

physical link between progenitor and explosion energy

Ruiter+12

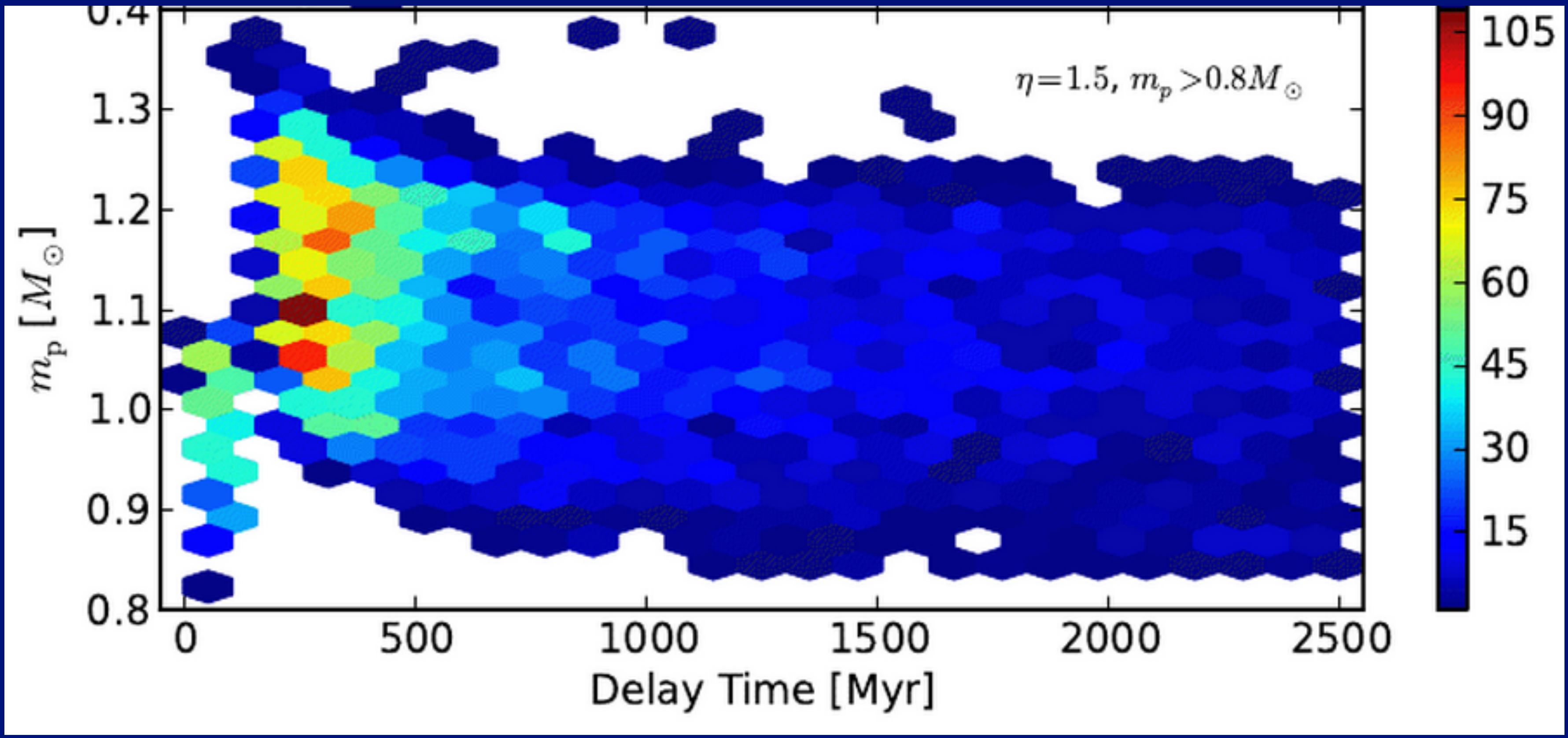
Ni^{56} mass

or

SN luminosity

or

stretch



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

~ 3 - 7%

~(1-2)x10^{-3} ~33

SN-Ia/Msun Msun