SNe as tracers of cosmic star formation

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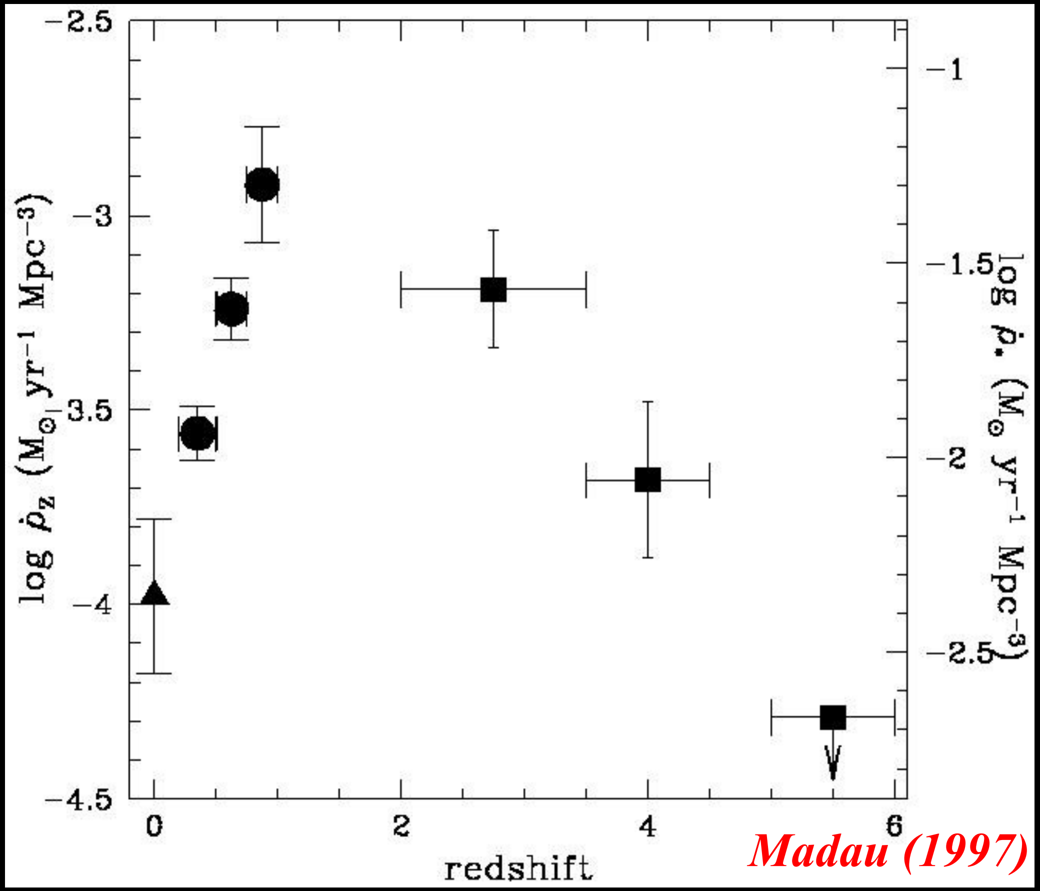
Sharp Eyes on European Skies, 23 Sept. 2015

"The knowledge of the star formation rate (SFR) throughout the universe as a function of space and time is one of the primary goal of galaxy formation and evolution studies"

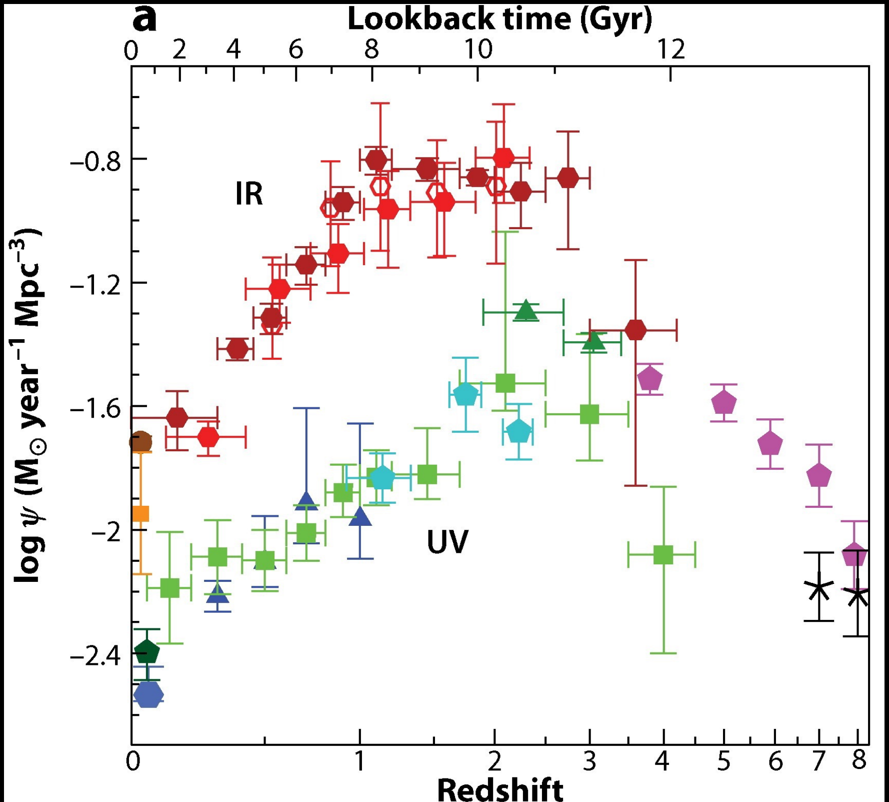
- How does the distribution of SFR evolve with redshift, are high-z galaxies forming stars more rapidly than quiescent spirals at z ~ 0 ?

- Are high-z galaxies obscured by dust in analogy with luminous IRAS starbursts ?

- Is there a characteristic epoch of star and elements formation in galaxies ?



- Consistent picture available from UV, optical and IR observations up to z ~ 8
- Are the data consistent with a universal IMF?
- Account for all the metals produced by the star-formation activity since Big Bang?



Madau P, Dickinson M. 2014.
Annu. Rev. Astron. Astrophys. 52:415–86

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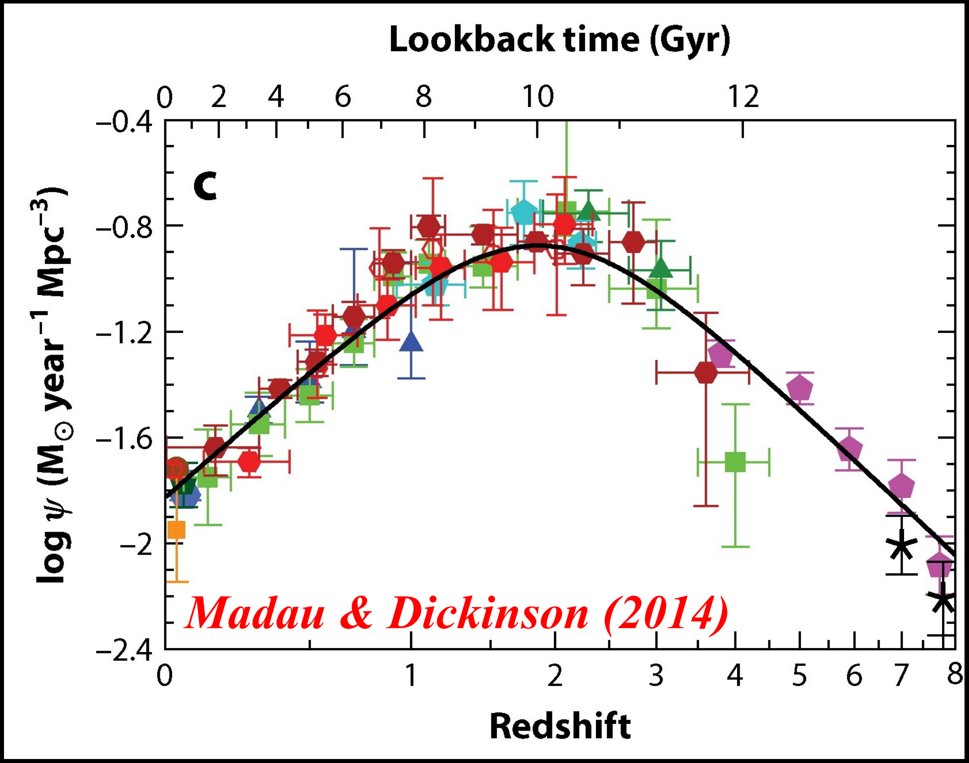
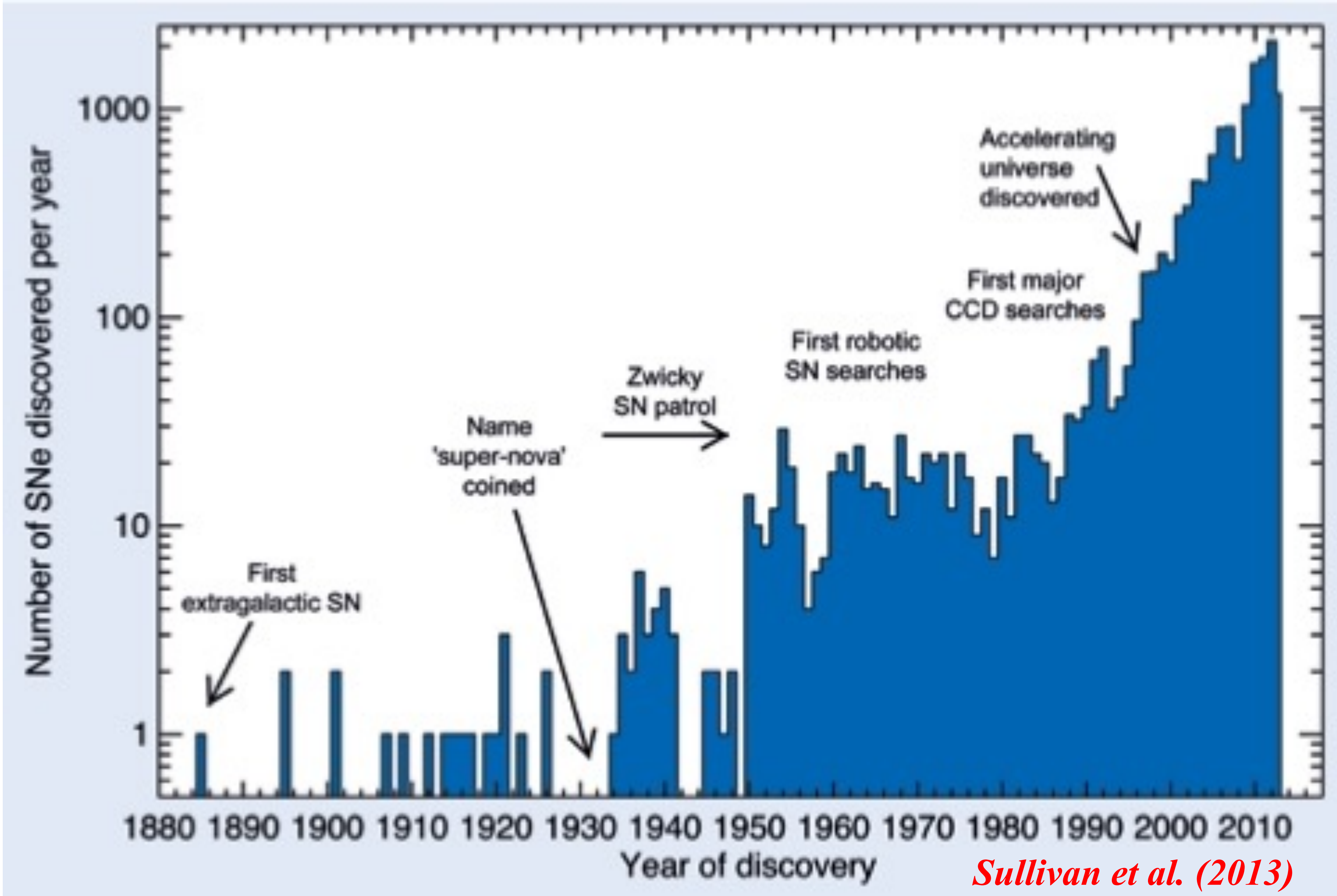
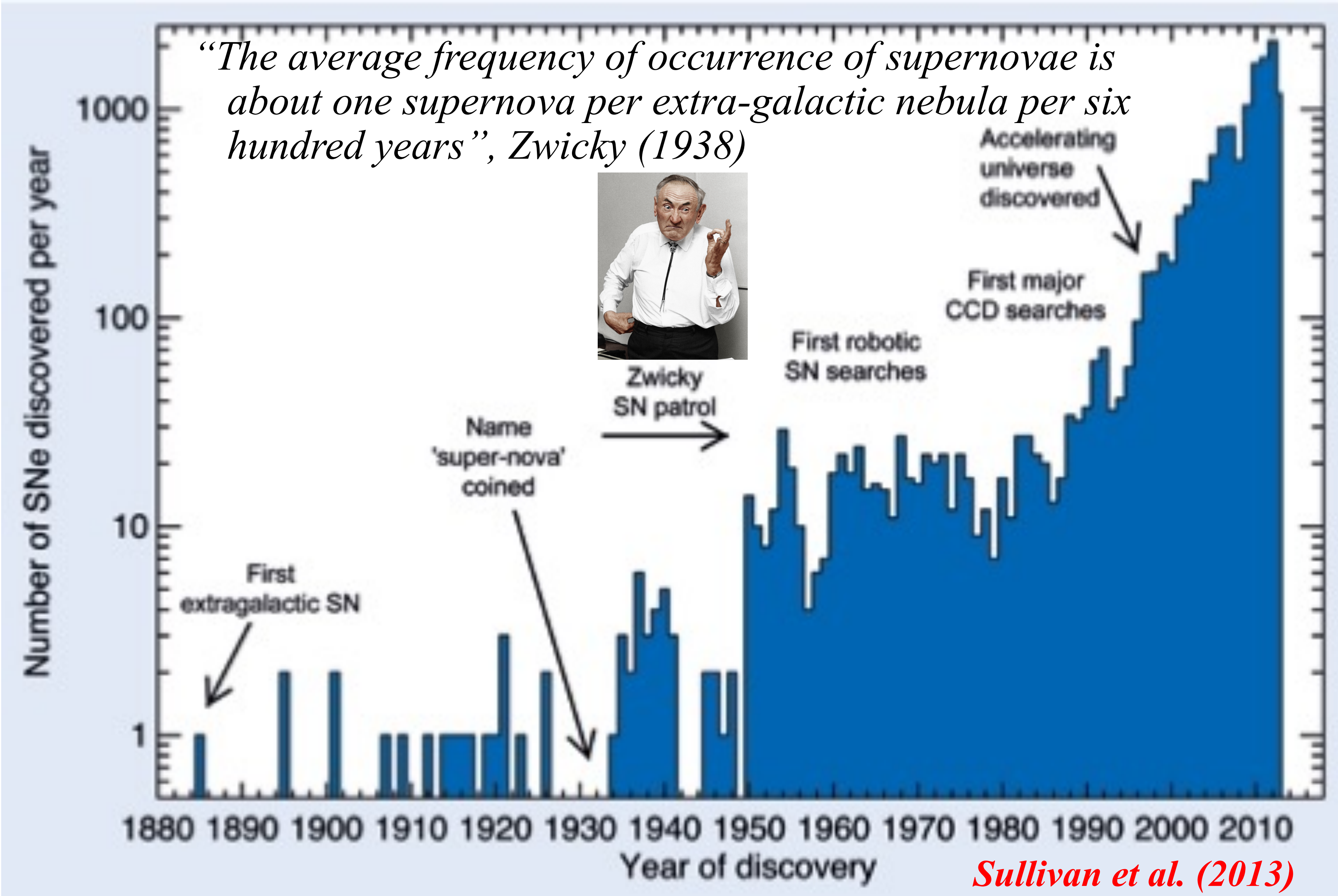


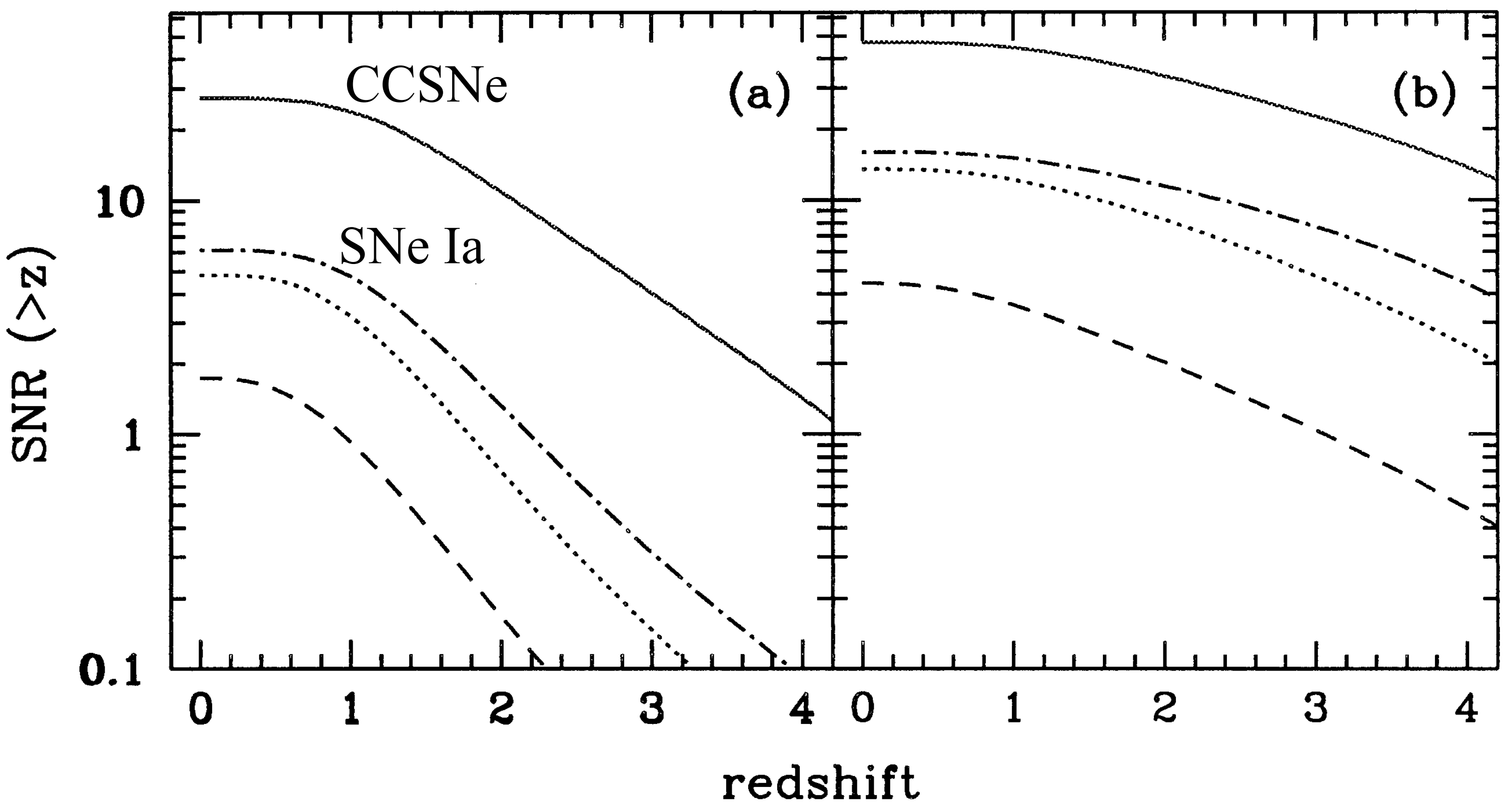


Sullivan et al. (2013)


"The average frequency of occurrence of supernovae is about one supernova per extra-galactic nebula per six hundred years", Zwicky (1938)
Accelerating universe discovered
First major CCD searches
First robotic SN searches
Zwicky SN patrol
Name 'super-nova' coined
First extragalactic SN
Number of SNe discovered per year
1000
100
10
1
1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010
Year of discovery
Sullivan et al. (2013)

“ Accurate measurements of the **frequency of SN events** in the range $0 < z < 1$ will be valuable probes of the nature of Type Ia progenitors and **the evolution of the stellar birth rate in the Universe**. The Next Generation Space Telescope should detect of order 20 Type II SNe per 4×4 arcmin field per year in the interval $1 < z < 4$ “

Madau, Della Valle & Panagia (1998)

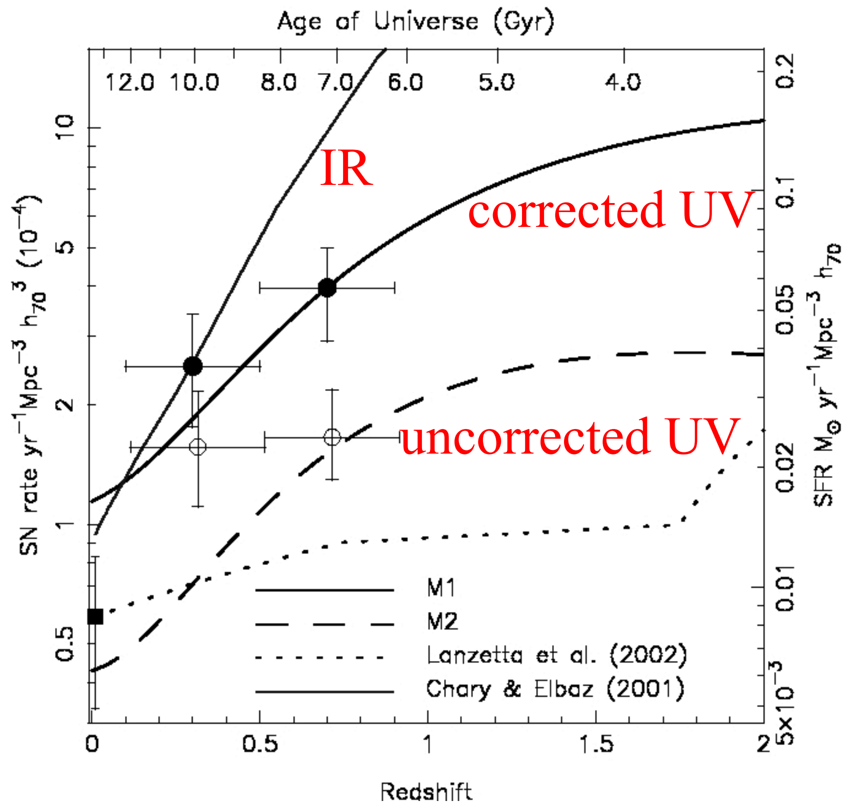


Cosmic star formation history from CCSN rates

- Core-collapse SNe come from massive stars ($\geq$8 $M_\odot$) with short lifetimes (< ~40 Myr)
- Direct relation between the SNR and SFR

$$R_{CC}(z) = k \times \rho_*(z),$$

$$k = \frac{\int_{M_l}^{M_u} \xi(M) dM}{\int_{0.1 M_\odot}^{125 M_\odot} M \xi(M) dM} \sim 0.007\ M_\odot^{-1}$$



- SNe can provide ***independent*** determination of the cosmic star formation rates

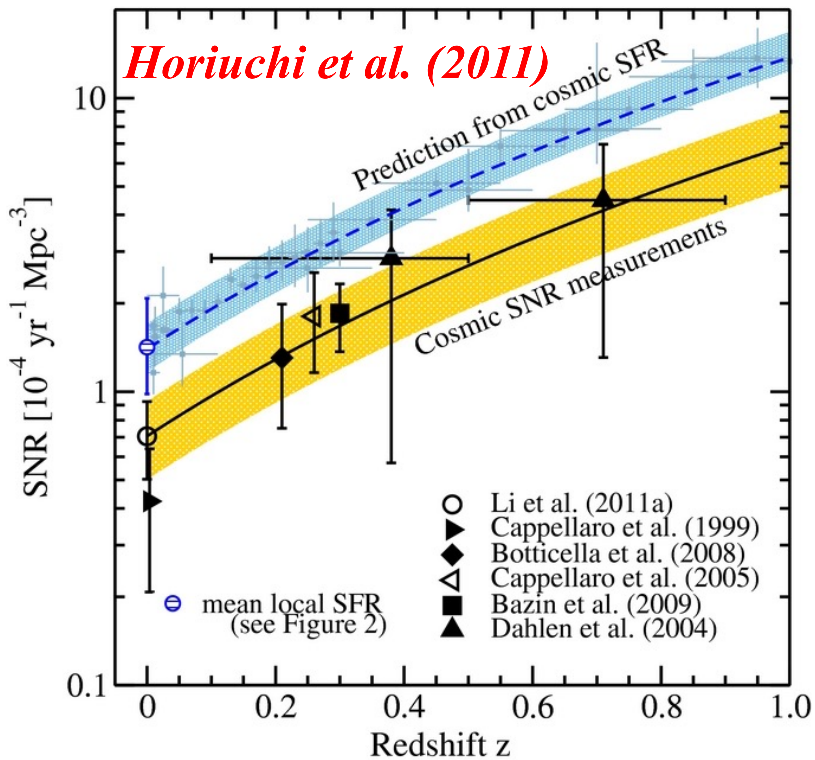
Dahlen et al. (1999, 2004)

Cosmic star formation history from CCSN rates

- *Measured* cosmic CCSN rate x2 lower than predicted from the *measured* SFRs
- Suggested resolutions
- ~50% of CCSNe optically ***faint*** or ***dark*** *?*
- Problems in our understanding of the star formation and/or SN rates ?

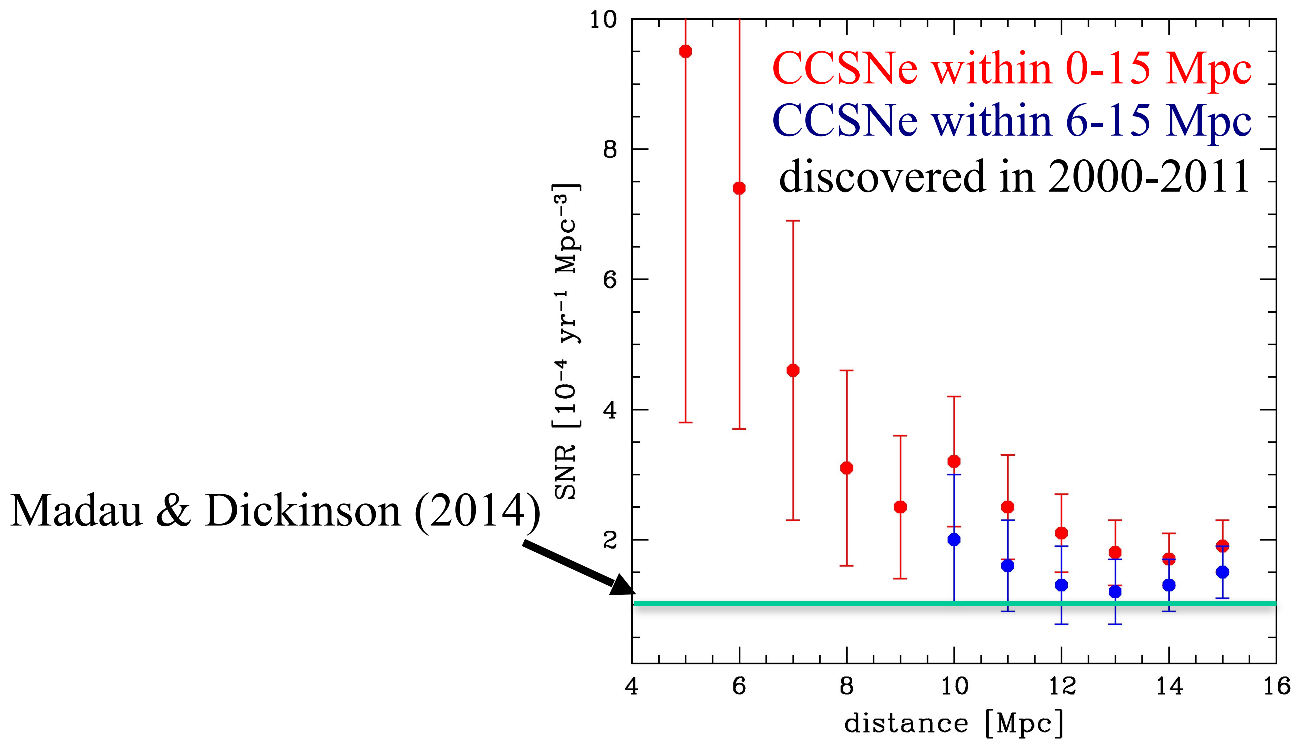
$$R_{CC}(z) = k \times \rho_*(z),$$

$$k = \frac{\int_{\mathcal{M}_l}^{\mathcal{M}_u} \xi(M) dM}{\int_{0.1\mathcal{M}_\odot}^{125\mathcal{M}_\odot} M\xi(M) dM} \sim 0.007\ \mathrm{M}_\odot^{-1}$$



Core-collapse SN rate in the very nearby volume

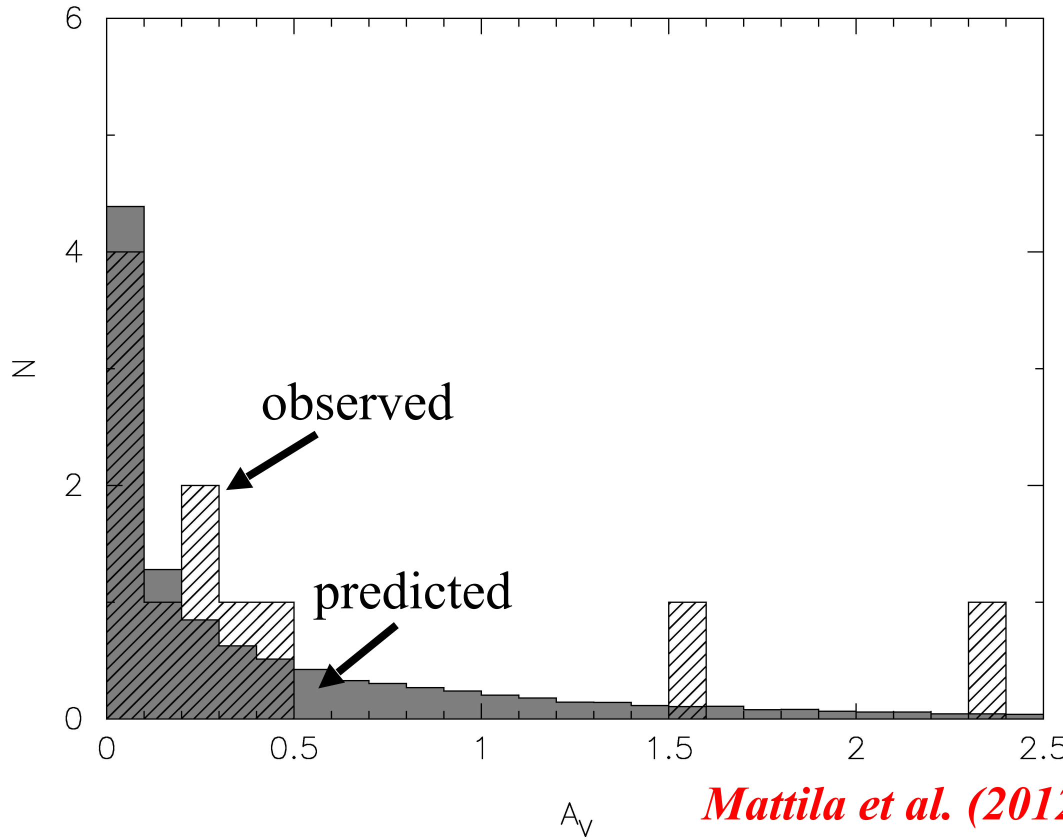
- Significant excess of SNe within ~6 Mpc caused by local SFR overdensity
- SN rate **1.5 ± 0.4 x 10^{-4} SNe yr^{-1} Mpc^{-3}** (between 6-15 Mpc)
- Consistent within the errors with the SFR at z=0 (Madau & Dickinson 2014)
- CCSN rates within 11 Mpc well matched by the Ha and FUV derived SFRs (Botticella+ 2012; Xiao & Eldridge 2015)



Mattila et al. (2012)

The SN budjet of "normal" galaxies

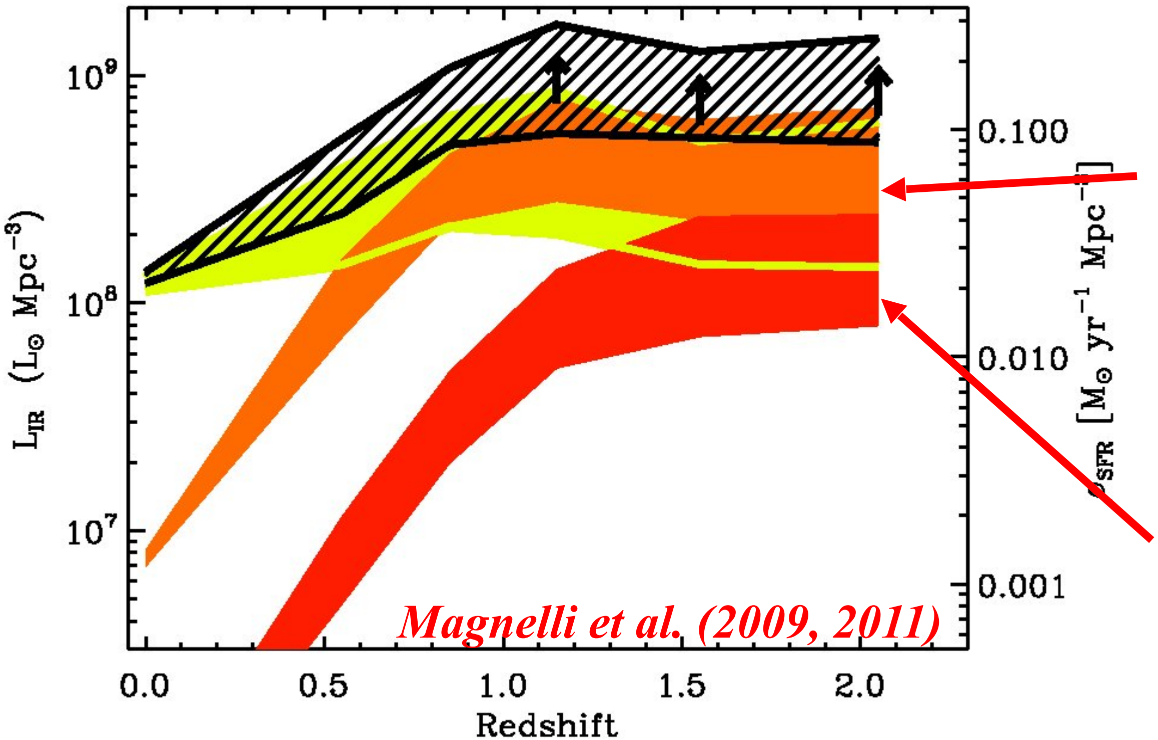
- Concentrate on 13 SNe within 12 Mpc with host galaxy i < 60
- Compare with predictions from a MC simulations (cf. Riello & Patat 2005)
- Two outliers from the expected A_V
  - SN 2002hh A_V(host) = 4.1
  - SN 2009hd A_V(host) = 3.7
- 2/13 have Av ~ 4 (expect ~0.3%)
- Missing SN fraction: **15% (5-36%)**



Mattila et al. (2012)

Correction for the "dark" SNe in U/LIRGs

- (Ultra)luminous IR galaxies locally rare but at z ~1-2 dominate the star formation
- Stars forming rapidly during a few x 100 Myr starburst episodes
- Large numbers of massive short lived stars exploding as CCSNe
- Missed by surveys due to large extinctions and concentration to nuclear regions



LIRGs: $10^{11} L_\odot < L_{IR} < 10^{12} L_\odot$

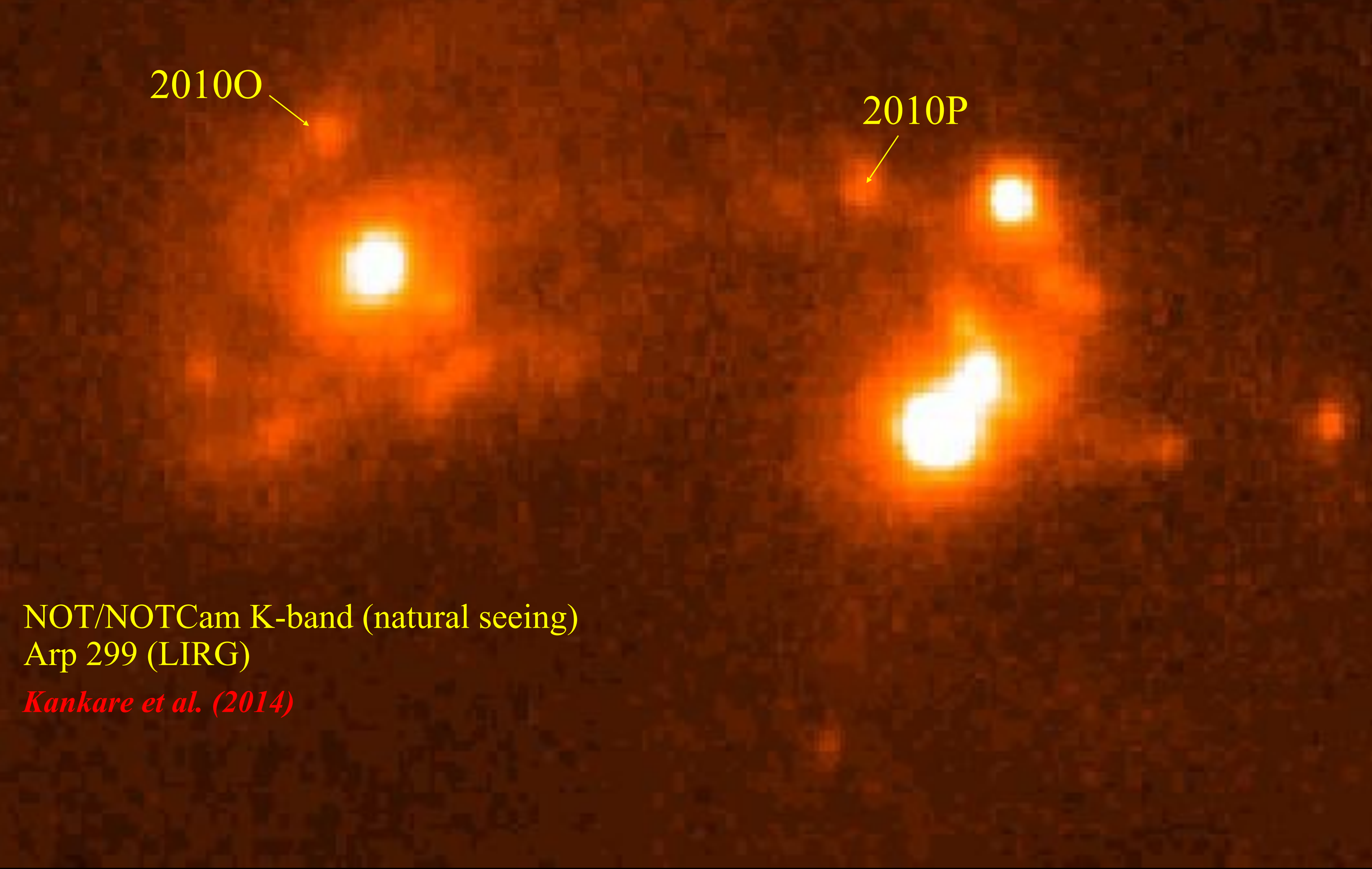
SFR a few x 10-100 $M_\odot$ yr^{-1}

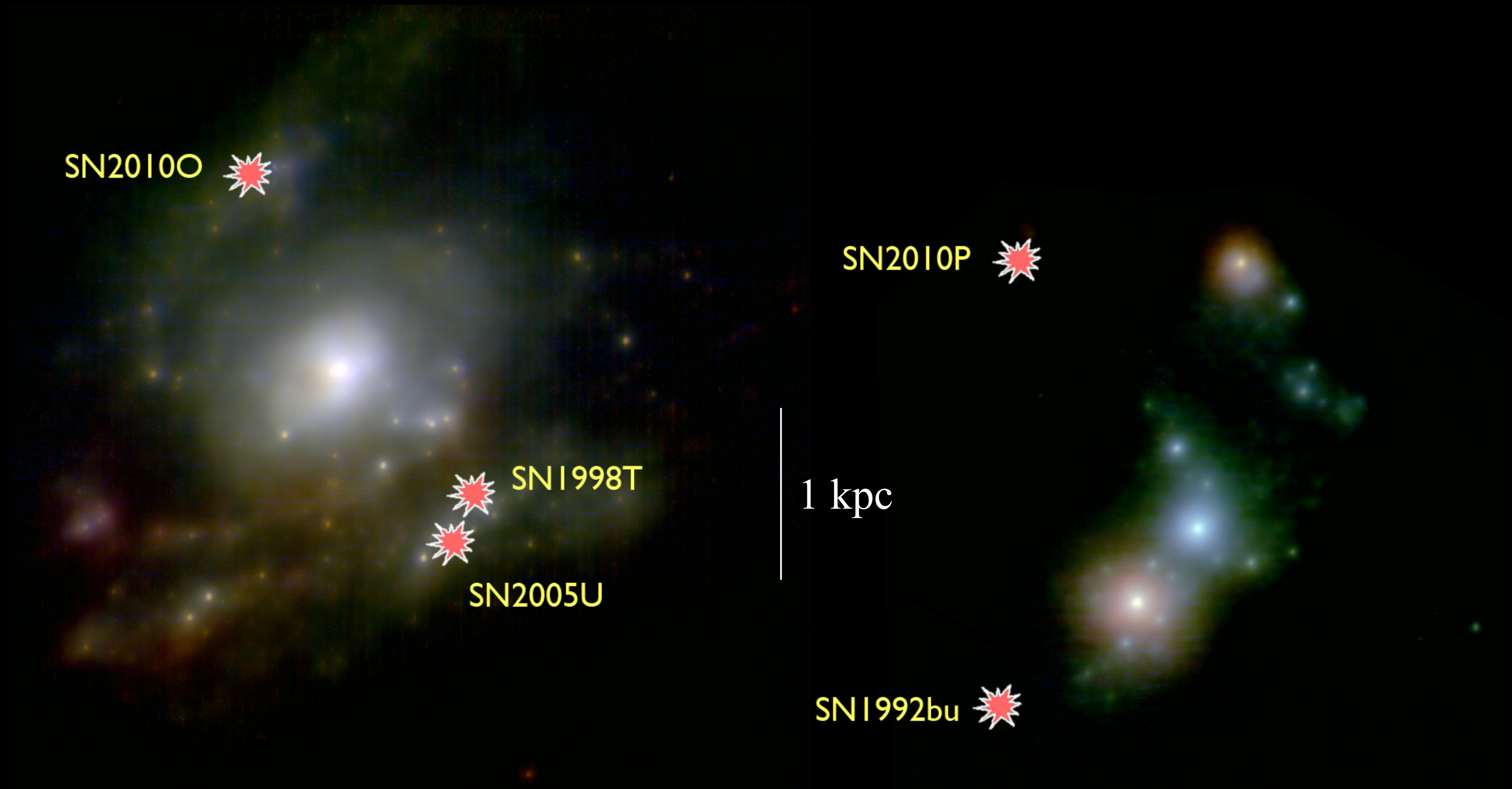
a few x 0.1-1 CCSNe yr^{-1}

ULIRGs: $10^{12} L_\odot < L_{IR} < 10^{13} L_\odot$

SFR a few x 100-1000 $M_\odot$ yr^{-1}

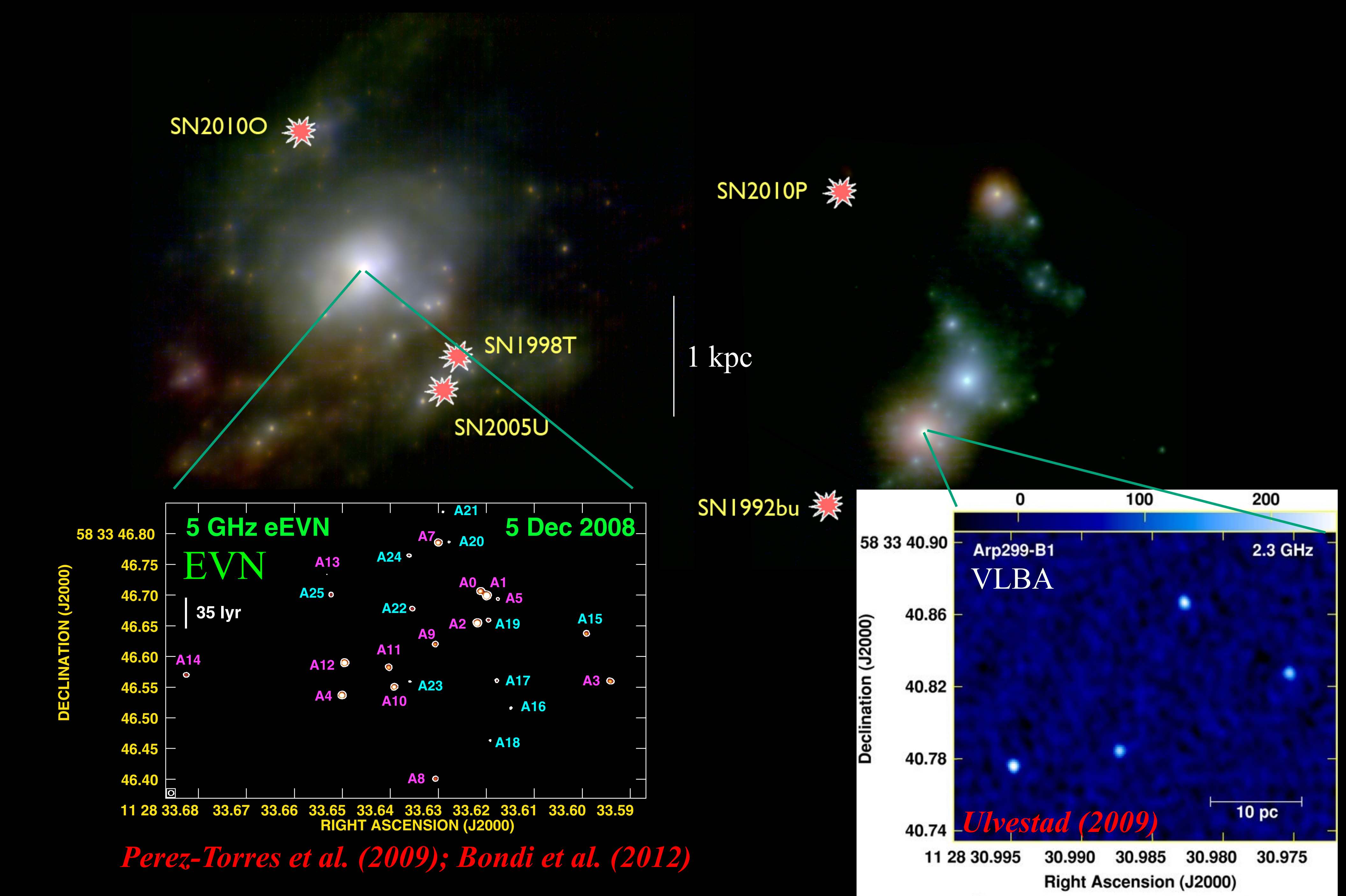
a few x 1-10 CCSNe yr^{-1}


2010O
2010P
NOT/NOTCam K-band (natural seeing)
Arp 299 (LIRG)
Kankare et al. (2014)

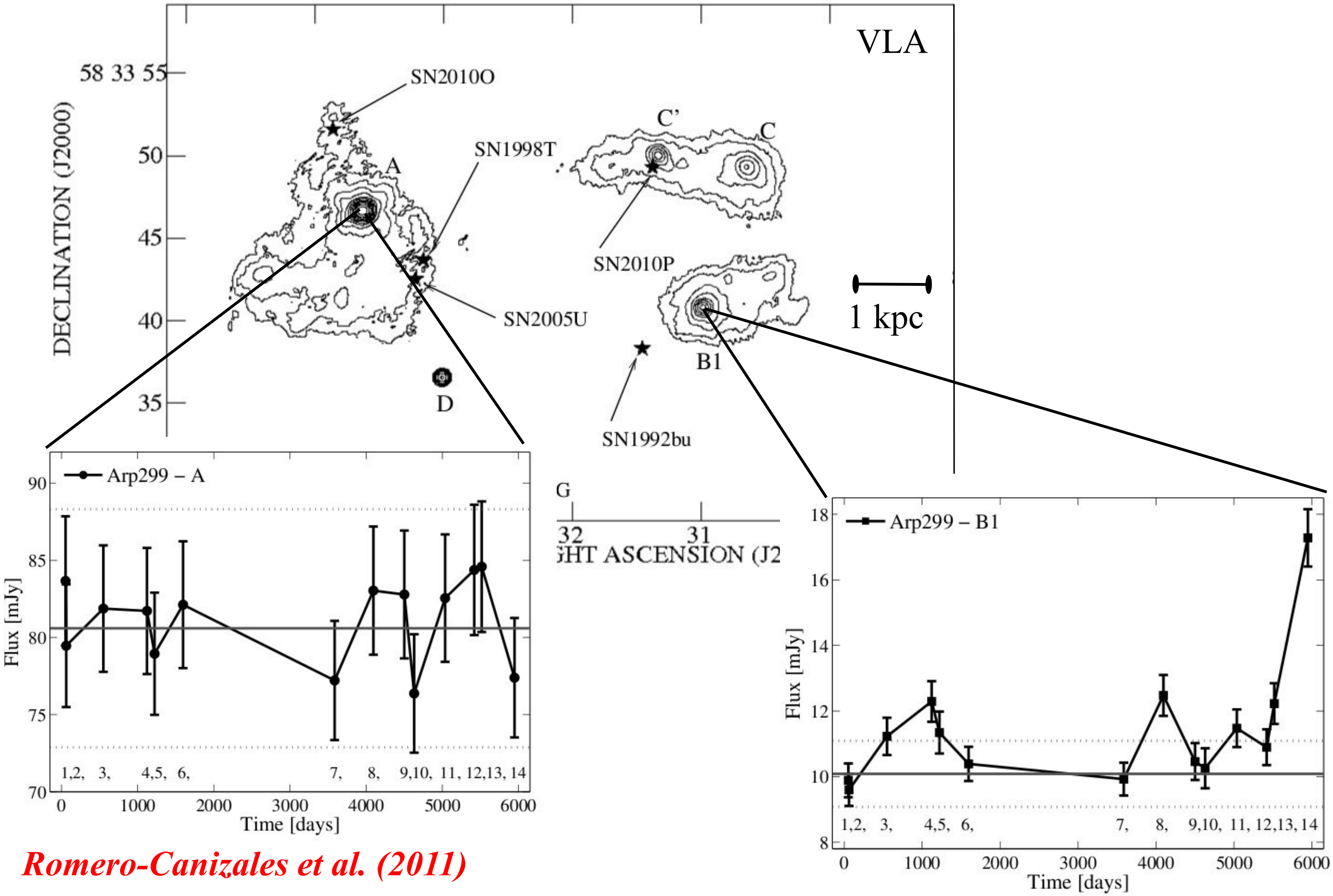


Gemini-N/Altair JHK-band (Adaptive Optics)

Kankare et al. (2014);
Ryder et al. (2014)



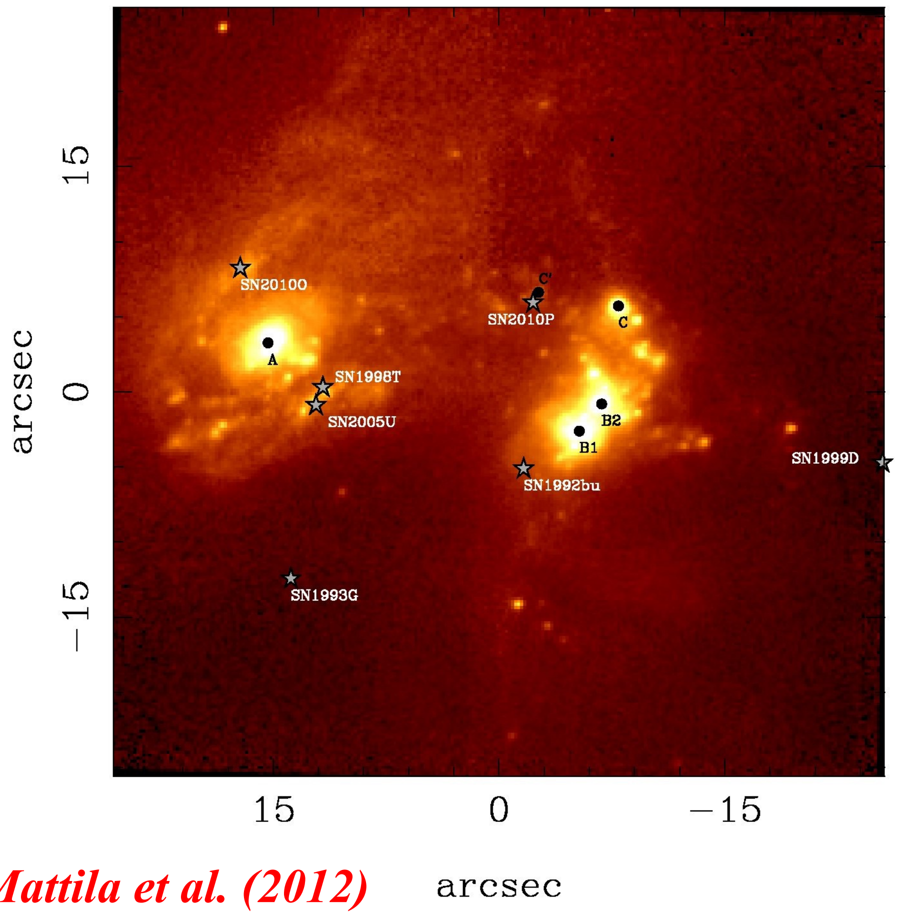
SN2010O
SN2010P
SN1998T
SN2005U
SN1992bu
1 kpc
5 GHz eEVN
5 Dec 2008
EVN
35 lyr
A0 A1 A2 A3 A4 A5 A7 A8 A9 A10 A11 A12 A13 A14 A15 A16 A17 A18 A19 A20 A21 A22 A23 A24 A25
58 33 46.80
46.75
46.70
46.65
46.60
46.55
46.50
46.45
46.40
DECLINATION (J2000)
11 28 33.68 33.67 33.66 33.65 33.64 33.63 33.62 33.61 33.60 33.59
RIGHT ASCENSION (J2000)
Perez-Torres et al. (2009); Bondi et al. (2012)
0 100 200
Arp299-B1
2.3 GHz
VLBA
58 33 40.90
40.86
40.82
40.78
40.74
Declination (J2000)
10 pc
Ulvestad (2009)
11 28 30.995 30.990 30.985 30.980 30.975
Right Ascension (J2000)



Romero-Canizales et al. (2011)

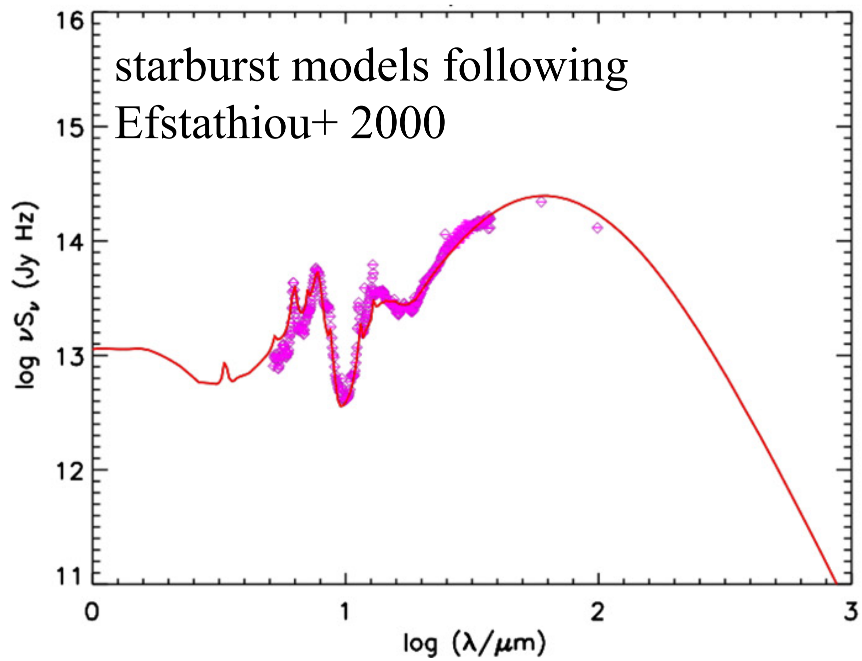
Correction for the "dark" SNe in U/LIRGs

- Estimates for the fraction of CCSNe missed by optical searches
- Use Arp 299 as a 'template' LIRG (large uncertainties due to small number stats)



Mattila et al. (2012)

Region	Age	τ_V	L_{IR} ($L_\odot$)	⟨SFR⟩	SNR
A	45 Myr	75	2.45×10^{11}	$90\ M_\odot\ yr^{-1}$	$0.76\ yr^{-1}$



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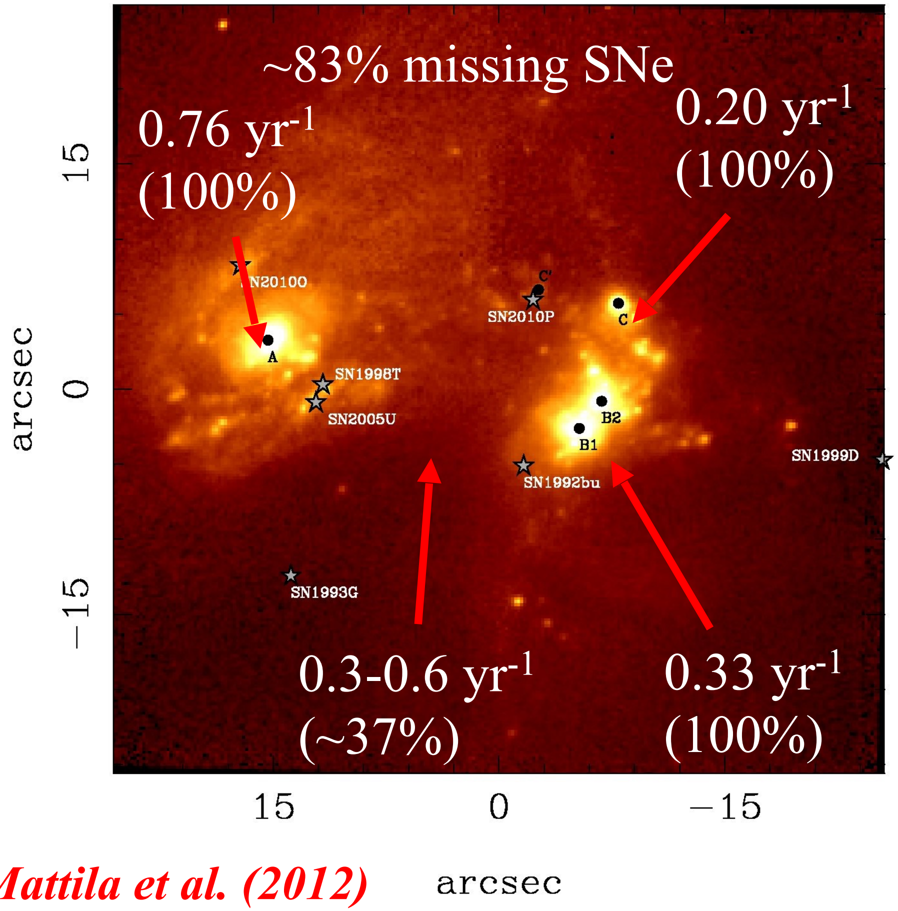
The SN Budget of Arp 299

Region	L_{IR}	Predicted SNR (yr^{-1})			Observed SNR (yr^{-1})	
	($\times 10^{11} L_{\odot}$)	IR	Radio	H_{α}	Optical+NIR	Optical
A	2.85	0.76	>0.8	...	...	...
B1+B2	1.46	0.33	$>0.28^{+0.27}_{-0.15}$	...	...	...
C+C′	0.73	0.20	$\sim 0.16 \pm 0.05$	...	$>0.07^{+0.17}_{-0.06}$	...
Circumnuclear	2.26	0.61	...	0.30	$>29^{+0.22}_{-0.14}$	$>0.29^{+0.22}_{-0.14}$
Total	7.3	1.90	>1.2	0.30	>0.36	>0.29

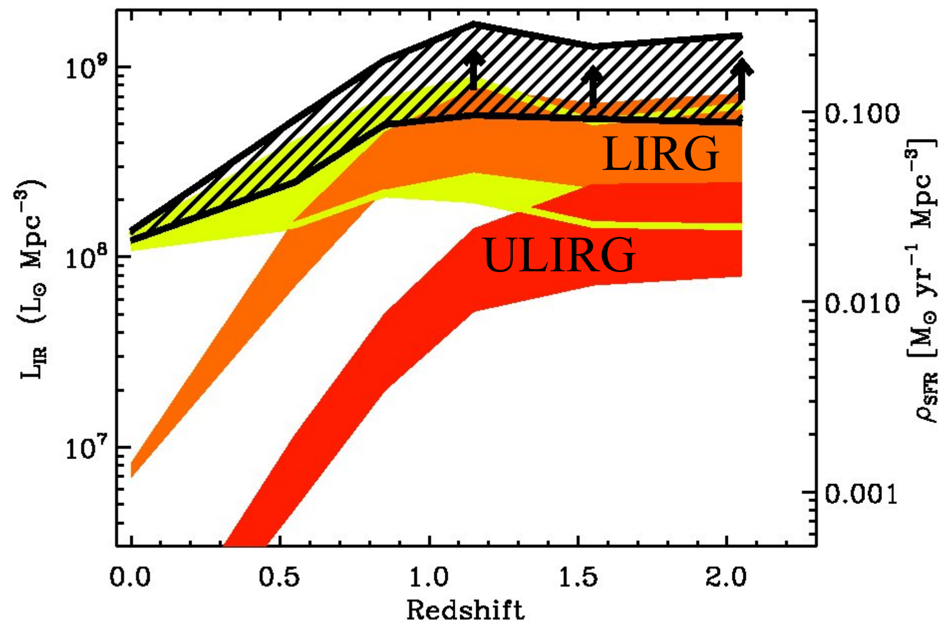
Mattila et al. (2012)

Correction for the "dark" SNe in U/LIRGs

- Estimates for the fraction of CCSNe missed by optical searches
- Use Arp 299 as a 'template' LIRG (large uncertainties due to small number stats)
- Adopt the number densities of U/LIRGs from Magnelli+ 2011



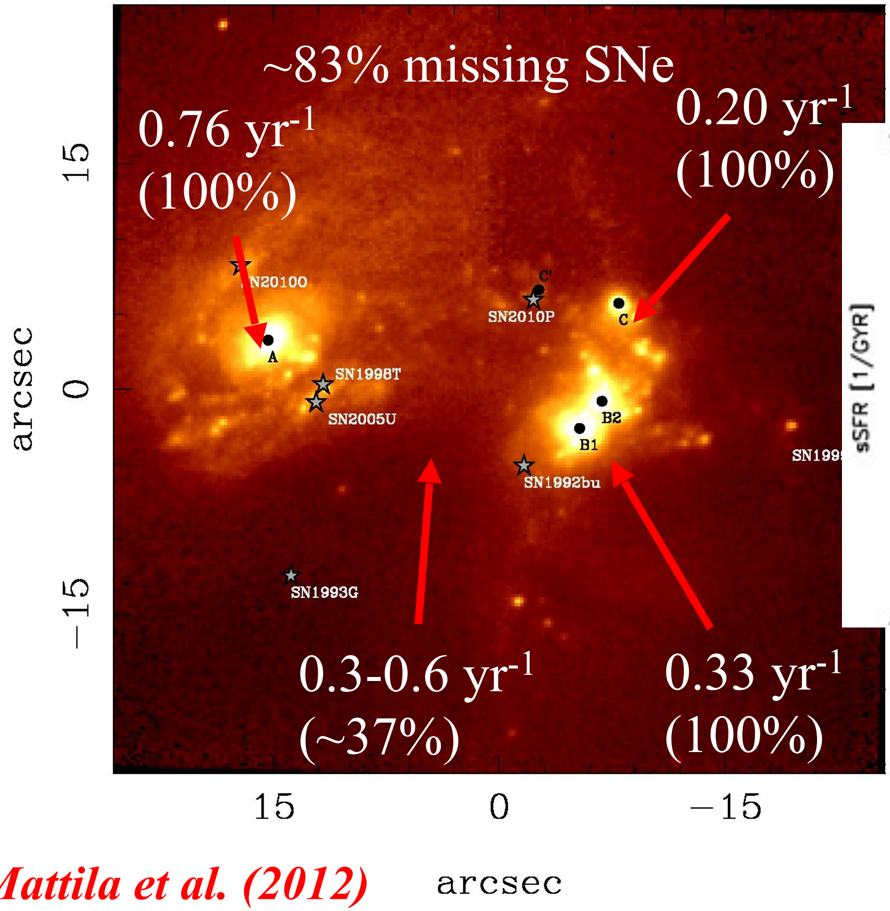
Mattila et al. (2012)



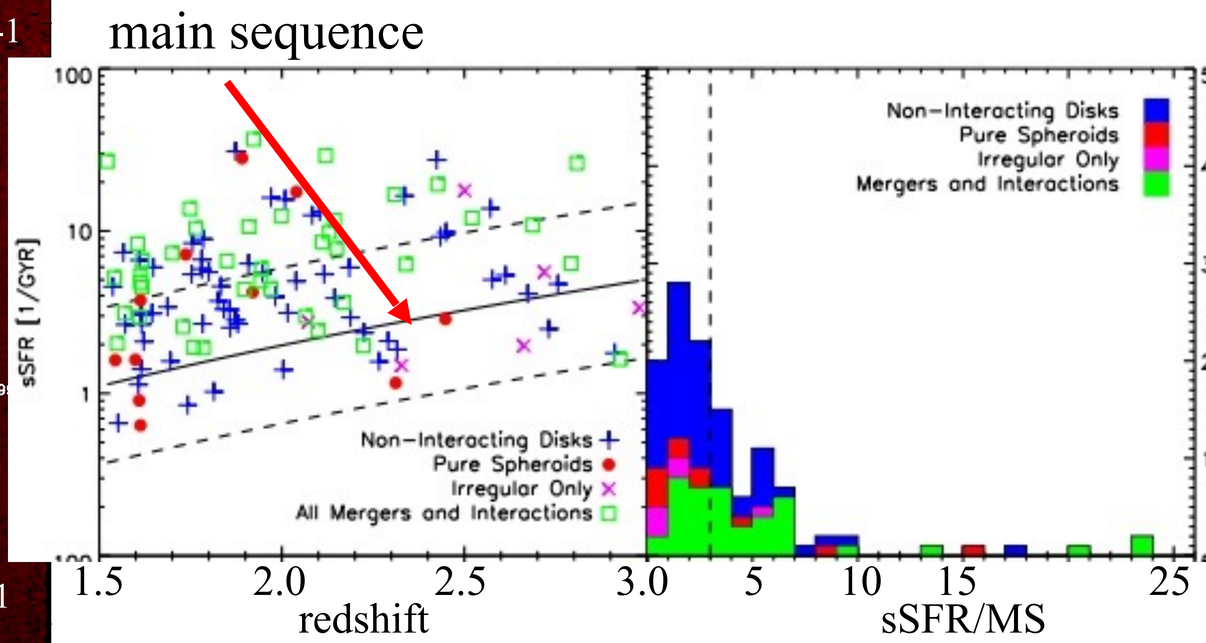
Magnelli et al. (2009, 2011)

Correction for the “dark” SNe in U/LIRGs

- **5-36%** missed in 'normal' galaxies, **83%** in local U/LIRGs
- **83%** missed in starbursting and **5-83%** in non-starbursting high-z U/LIRGs
- Fraction of starburst U/LIRGs 42% at z = 1.5-2 and 100% locally (Kartatepe+ 2012)



Mattila et al. (2012)



Kartaltepe et al. (2011)

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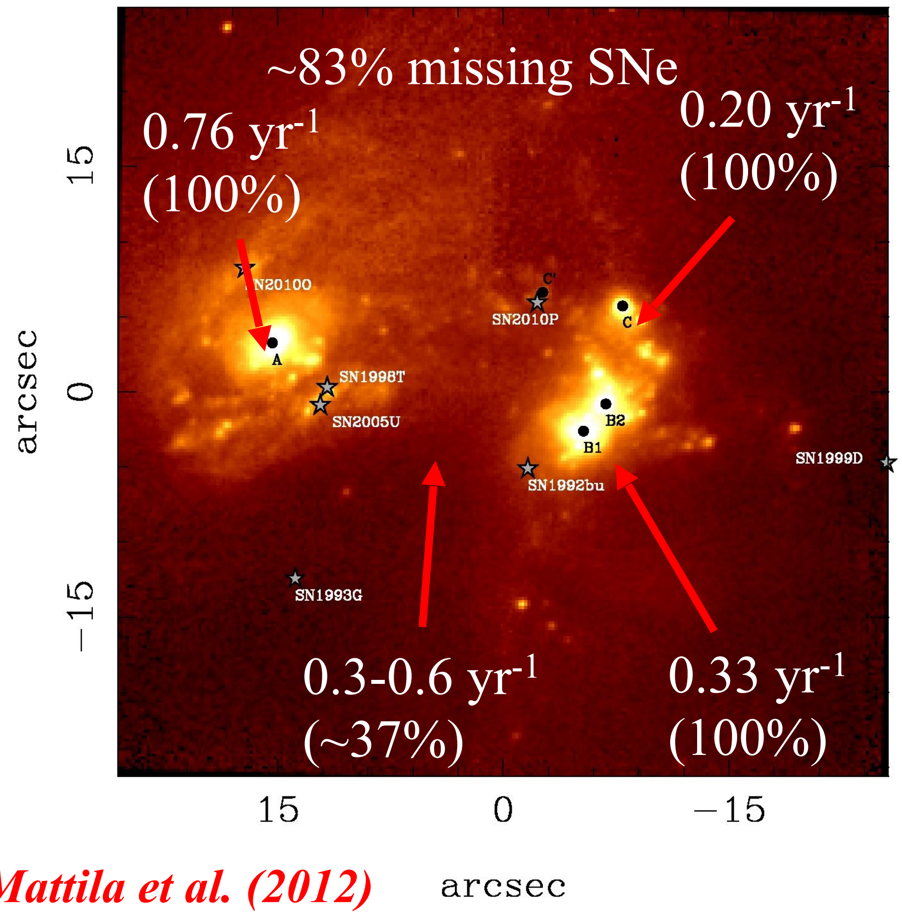
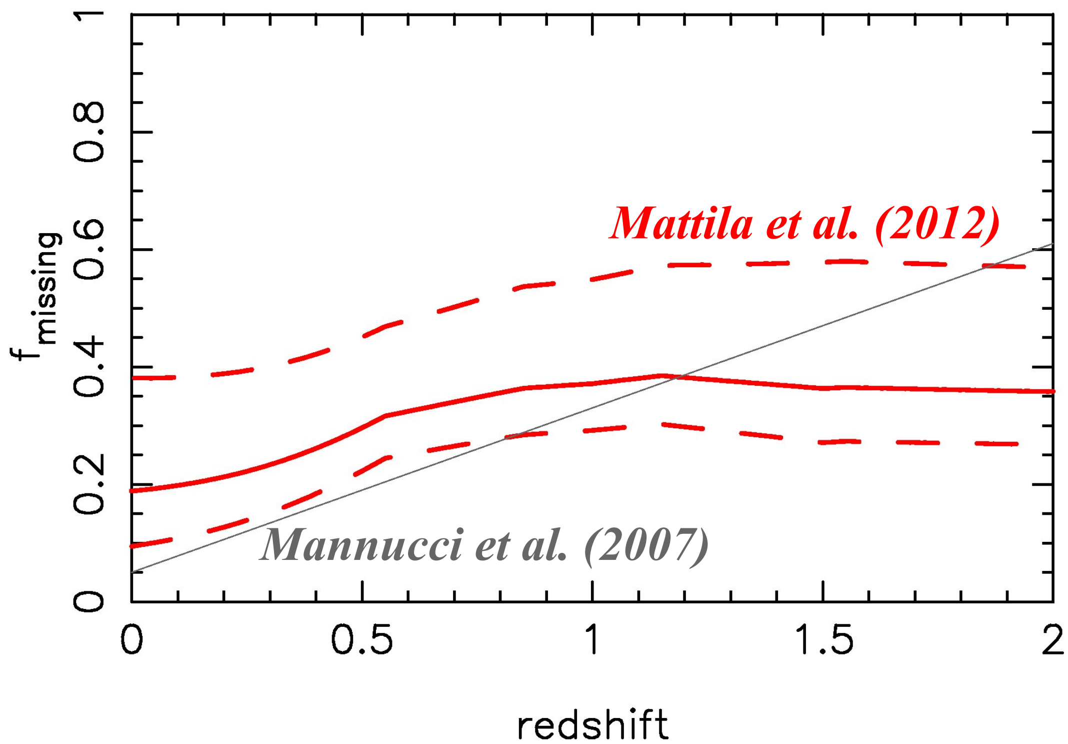
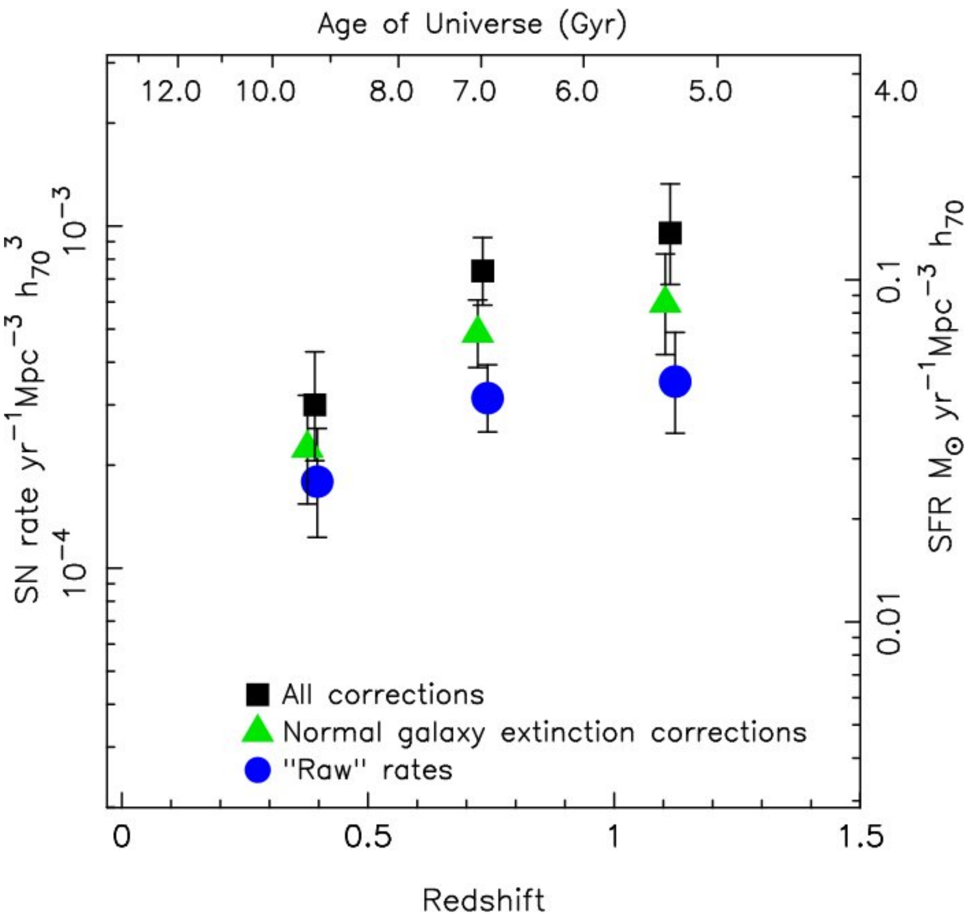




Mattila et al. (2012)

Effects of missing SNe on cosmic CCSN rates

- Melinder 2012 and Dahlen 2012 CCSN rates corrected for the "missing" SNe
- CCSN rates at z ~ 0.4-1.1 consistent with those expected from the cosmic SFR
- Systematic uncertainties in the CCSN rates significant at all redshifts



Melinder et al. (2012)
Dahlen et al. (2012)

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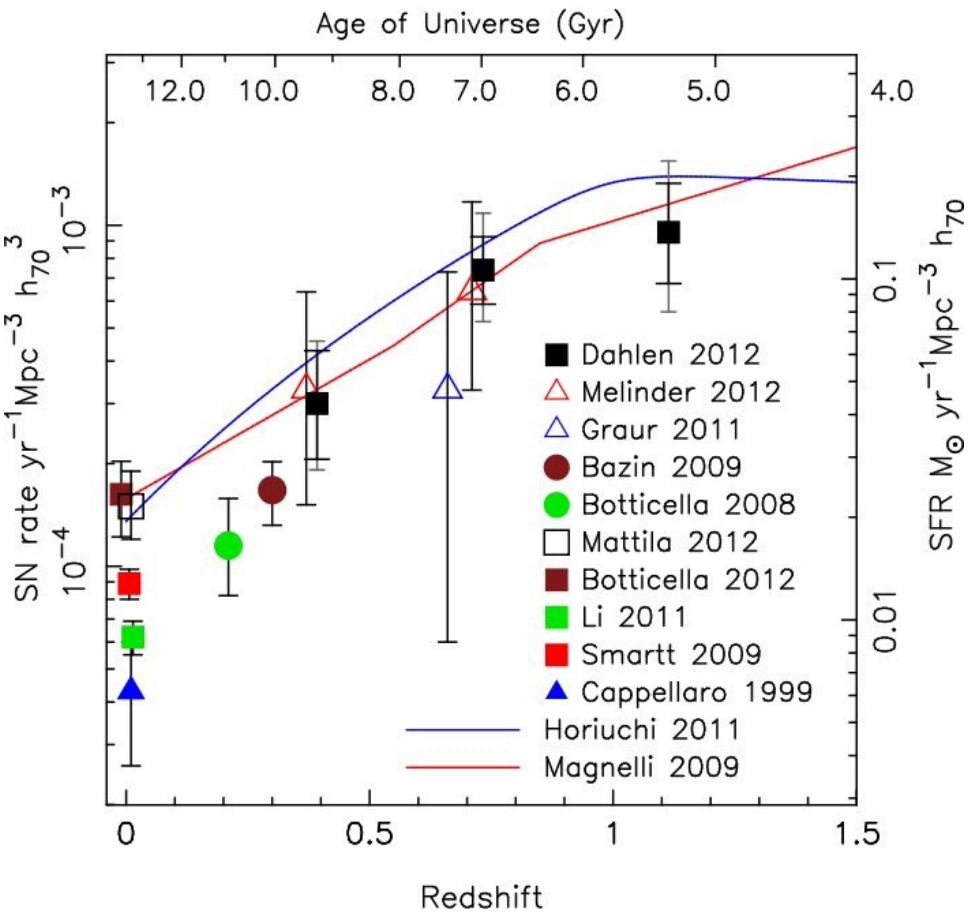

Melinder et al. (2012)
Dahlen et al. (2012)

Error Sources

	Redshift $0.1 < z < 0.5$	Redshift $0.5 < z < 0.9$	Redshift $0.9 < z < 1.3$
Subtype fraction	$^{+0.9\%}_{-1.4\%}$	$^{+3.7\%}_{-4.2\%}$	$^{+13.9\%}_{-15.0\%}$
Faint ($M > -15$) fraction	$^{+13.5\%}_{-10.0\%}$	$^{+18.6\%}_{-13.2\%}$	$^{+14.0\%}_{-13.5\%}$
Peak magnitudes	$^{+4.7\%}_{-4.0\%}$	$^{+8.7\%}_{-7.7\%}$	$^{+10.5\%}_{-9.7\%}$
Redshift uncertainty	$^{+4.1\%}_{-2.7\%}$	$^{+1.1\%}_{-1.8\%}$	$^{+2.5\%}_{-1.7\%}$
Type determination	$^{+7.5\%}_{-9.2\%}$	$^{+7.8\%}_{-6.4\%}$	$^{+6.1\%}_{-13.2\%}$
Extinction correction	$^{+9.7\%}_{-4.6\%}$	$^{+14.5\%}_{-6.9\%}$	$^{+15.5\%}_{-6.8\%}$
Extinction laws	$^{+6.5\%}_{-6.3\%}$	$^{+8.8\%}_{-4.0\%}$	$^{+11.8\%}_{-0.2\%}$
Missing fraction	$^{+28.0\%}_{-9.6\%}$	$^{+33.0\%}_{-10.3\%}$	$^{+42.0\%}_{-11.6\%}$
Systematic summed	$^{+34.6\%}_{-19.0\%}$	$^{+43.3\%}_{-21.6\%}$	$^{+51.8\%}_{-29.3\%}$
Statistical errors	$^{+42.8\%}_{-31.2\%}$	$^{+25.2\%}_{-20.5\%}$	$^{+39.3\%}_{-29.2\%}$

Notes. Different sources contributing to systematic uncertainties. For the summed errors, the difference sources are added in quadrature. See the text for details.

Dahlen et al. (2012)

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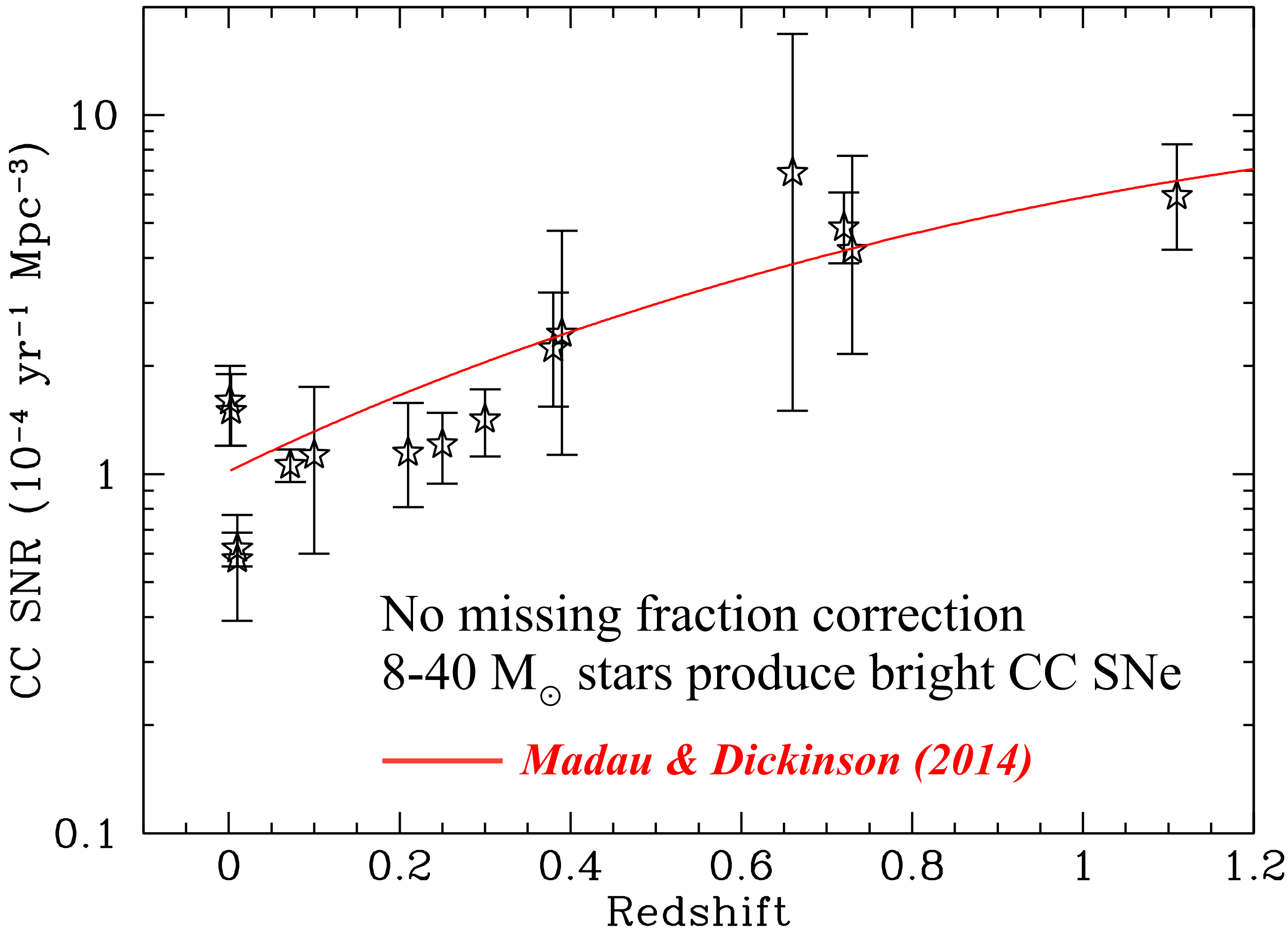
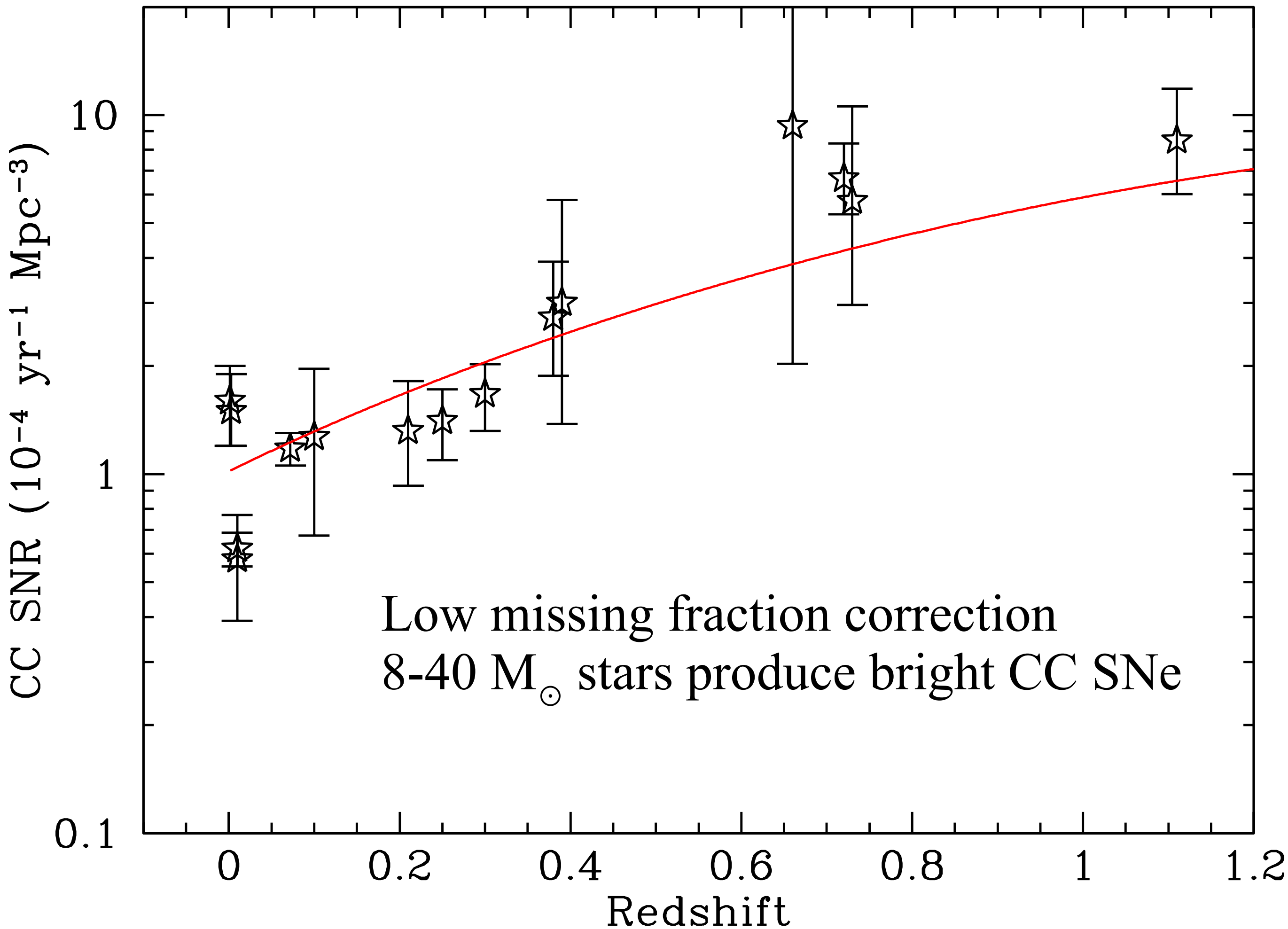
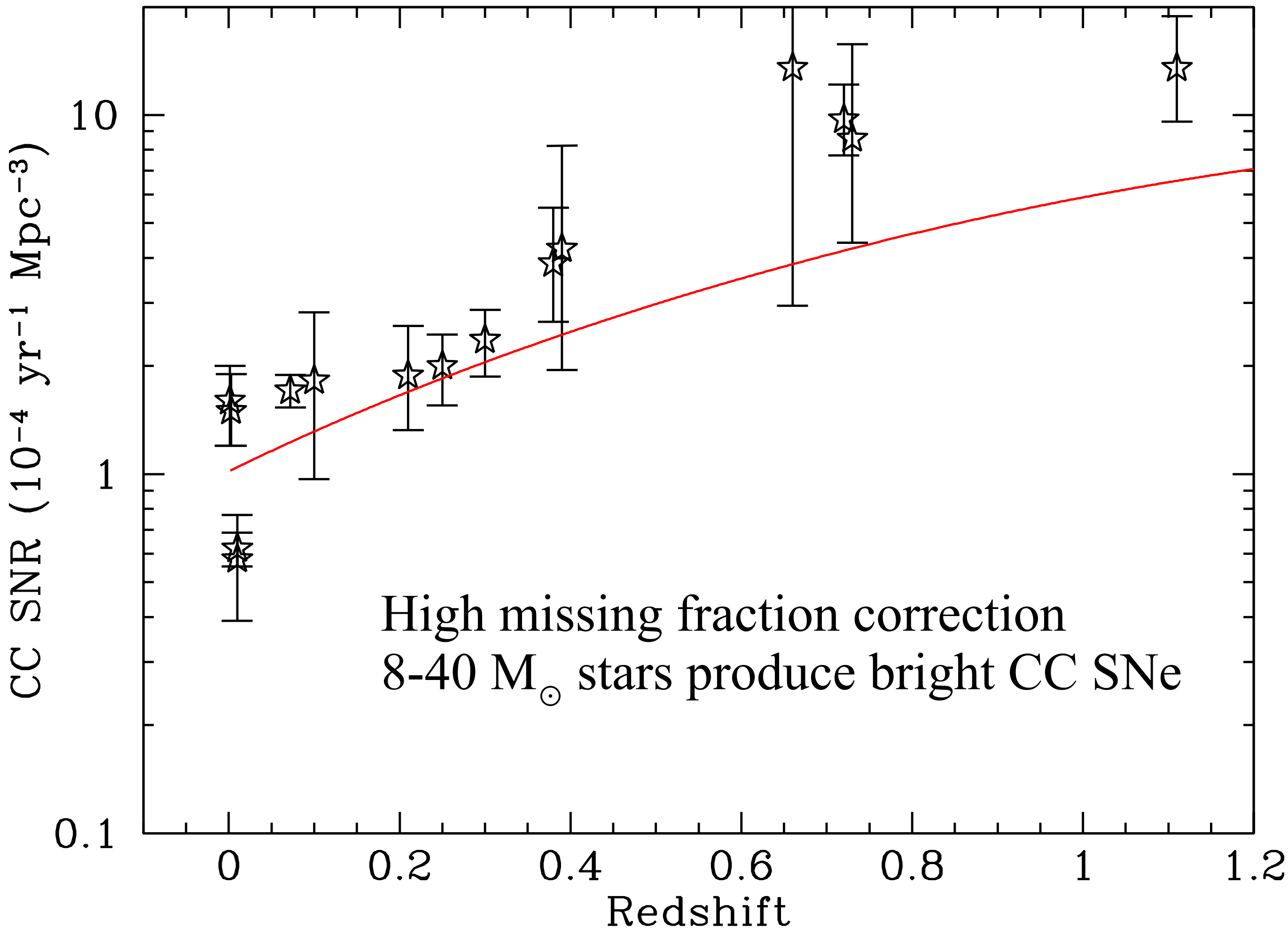
Dahlen et al. (2012)



CCSN rates: Botticella+ 2012; Mattila+ 2012; Smartt+ 2009; Cappellaro+ 1999; Li+ 2011; Taylor+ 2014; Botticella+ 2008; Cappellaro+ 2015; Bazin+ 2009; Graur+ 2011; Melinder+ 2012; Dahlen+ 2012


CC SNR (10^{-4} yr^{-1} Mpc^{-3})
10
1
0.1
0
0.2
0.4
0.6
0.8
1
1.2
Redshift
Low missing fraction correction
8-40 $M_\odot$ stars produce bright CC SNe


CC SNR (10^{-4} yr^{-1} Mpc^{-3})
Redshift
10
1
0.1
0
0.2
0.4
0.6
0.8
1
1.2
High missing fraction correction
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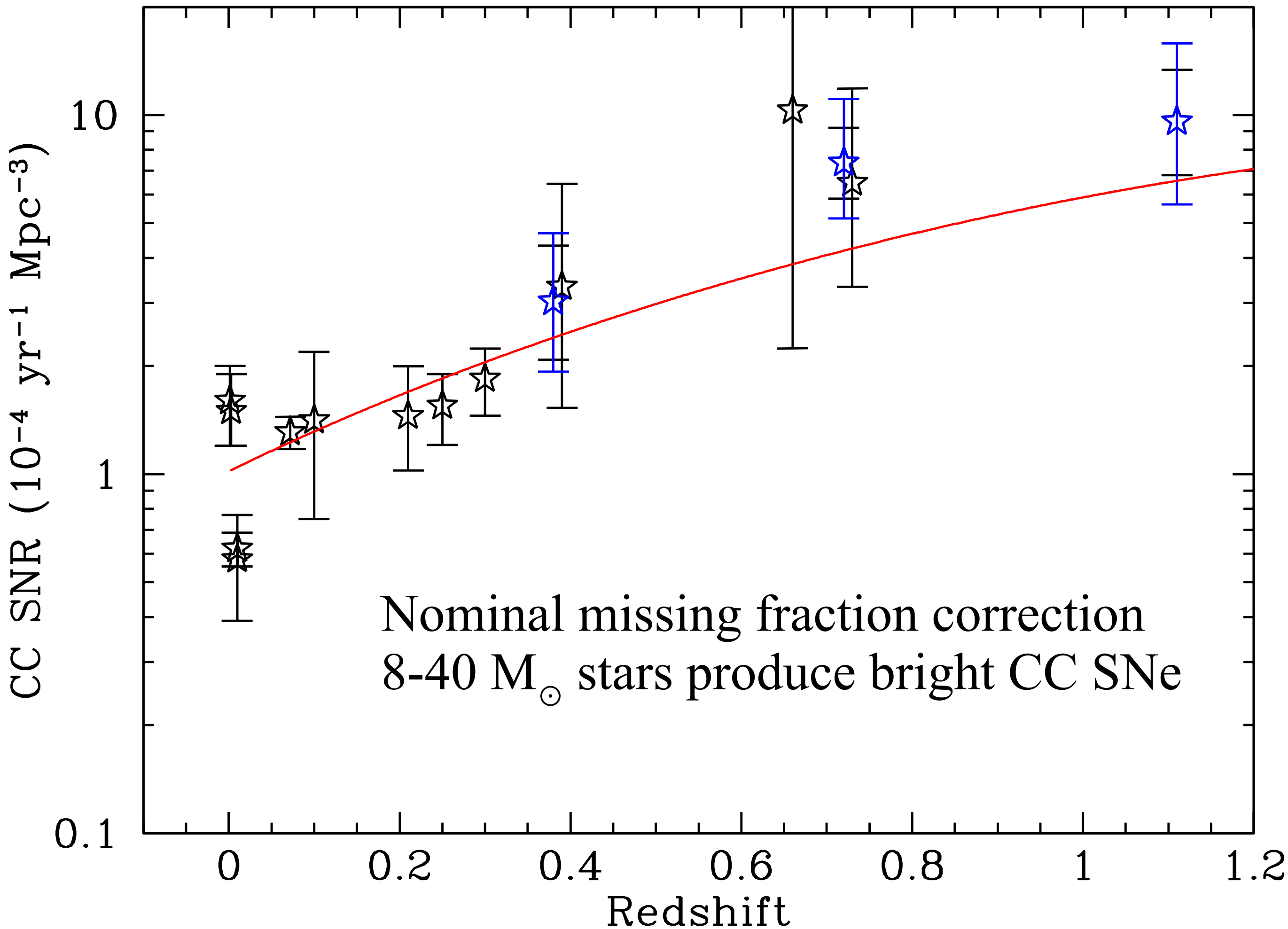

Nominal missing fraction correction
8-40 $M_\odot$ stars produce bright CC SNe
CC SNR (10^{-4} yr^{-1} Mpc^{-3})
Redshift
0.1
1
10
0
0.2
0.4
0.6
0.8
1
1.2

THE RATE OF CORE COLLAPSE SUPERNOVAE TO REDSHIFT 2.5 FROM THE CANDELS AND CLASH SUPERNOVA SURVEYS

Louis-Gregory Strolger[1], Tomas Dahlen[1,†], Steven A. Rodney[2], Or Graur[3,4], Adam G. Riess[2], Curtis McCully[5,6], Swara Ravindranath[1], Bahram Mobasher[7], and A. Kristin Shahady[8]

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ABSTRACT

The Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS) and Cluster Lensing And Supernova survey with Hubble (CLASH) multi-cycle treasury programs with the *Hubble Space Telescope* (*HST*) have provided new opportunities to probe the rate of core-collapse supernovae (CCSNe) at high redshift, now extending to $z \approx 2.5$. Here we use a sample of approximately 44 CCSNe to determine volumetric rates, R_{CC}, in six redshift bins in the range $0.1 < z < 2.5$. Together with rates from our previous *HST* program, and rates from the literature, we trace a more complete history of $R_{CC}(z)$, with $R_{CC} = 0.72 \pm 0.06$ yr^{-1} Mpc^{-3} 10^{-4} h_{70}^3 at $z < 0.08$, and increasing to $3.7^{+3.1}_{-1.6}$ yr^{-1} Mpc^{-3} 10^{-4} h_{70}^3 to $z \approx 2.0$. The statistical precision in each bin is several factors better than than the systematic error, with significant contributions from host extinction, and average peak absolute magnitudes of the assumed luminosity functions for CCSN types. Assuming negligible time delays from stellar formation to explosion, we find these composite CCSN rates to be in excellent agreement with cosmic star formation rate density (SFRs) derived largely from dust-corrected rest-frame UV emission, with a scaling factor of $k = 0.0091 \pm 0.0017\, M_{\odot}^{-1}$, and inconsistent (to $> 95\%$ confidence) with SFRs from IR luminous galaxies, or with SFR models that include simple evolution in the initial mass function over time. This scaling factor is expected if the fraction of the IMF contributing to CCSN progenitors is in the 8 to 50 $M_{\odot}$ range. It is not supportive, however, of an upper mass limit for progenitors at $< 20\, M_{\odot}$.

Subject headings: supernovae: general, surveys

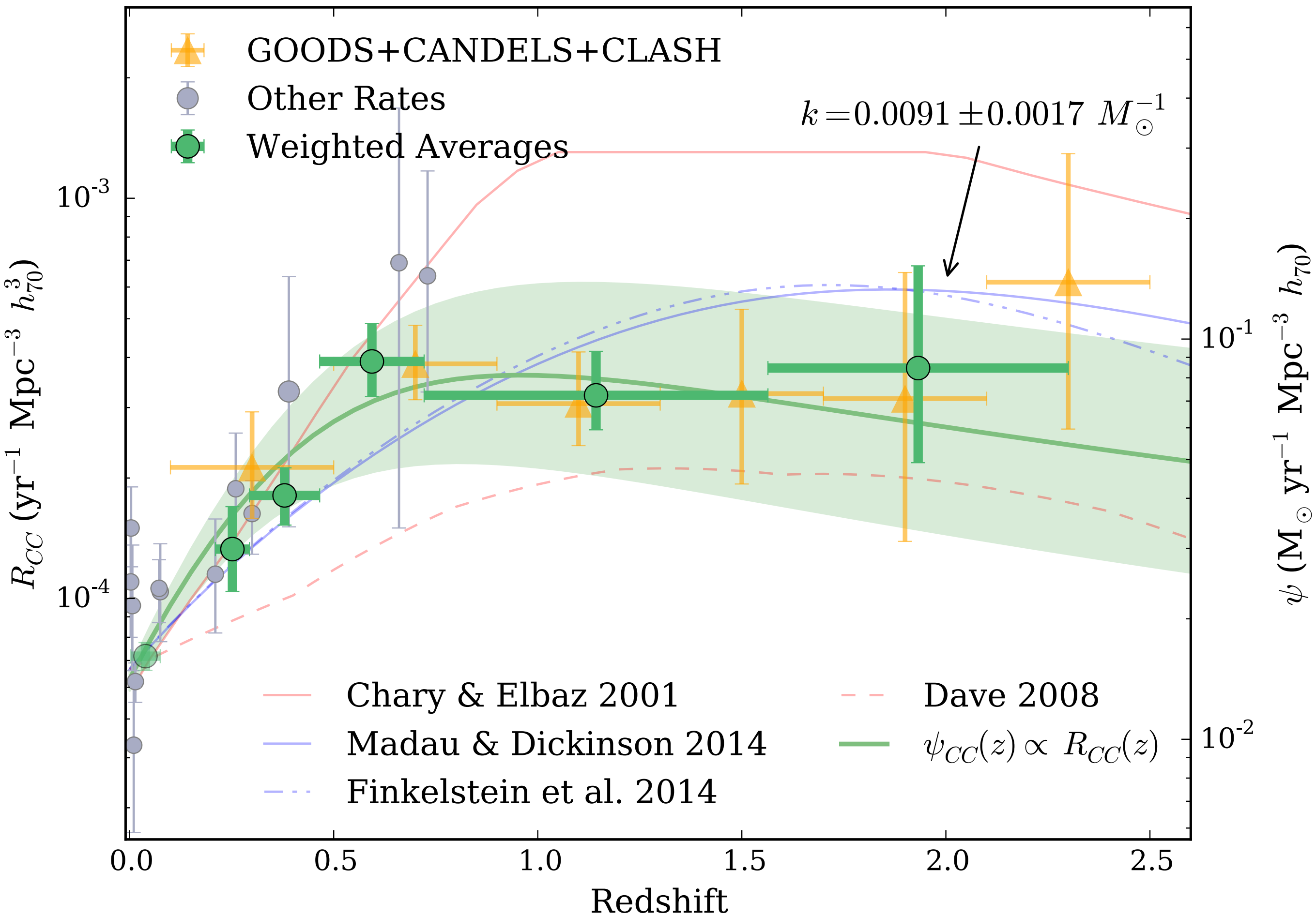

FIG. 6.— Rates from our group in comparison from other CCSN rates in the literature. *Green circles:* weighted average rates in six equalized redshift bins. *Right Ordinate and Lines:* star-formation rate density models, scaled to best match the Madau & Dickinson SFR to all CCSN rate measures, with $k = 0.0091 \pm 0.0017\, M_\odot^{-1}$. Also shown is the SFR model derived from the CCSNe rates (green) using the Madau & Dickinson parameterization.

Summary

- Observed CCSN rates consistent with the expectations from the cosmic SFH
- Provide a useful consistency check - counting SNe independent from many assumptions and biases with the more conventional methods and can yield also useful information on the SN progenitors
- CCSNe are missed by rest-frame optical surveys in dusty environments - an increased sample and better understanding of SNe in U/LIRGs can allow more detailed comparison between CCSN rates and cosmic SF history
- The future IR searches will extend CCSN rates beyond the peak of the cosmic SFH