Supernovae as tracers of cosmic star formation

Seppo Mattila
University of Turku, Finland

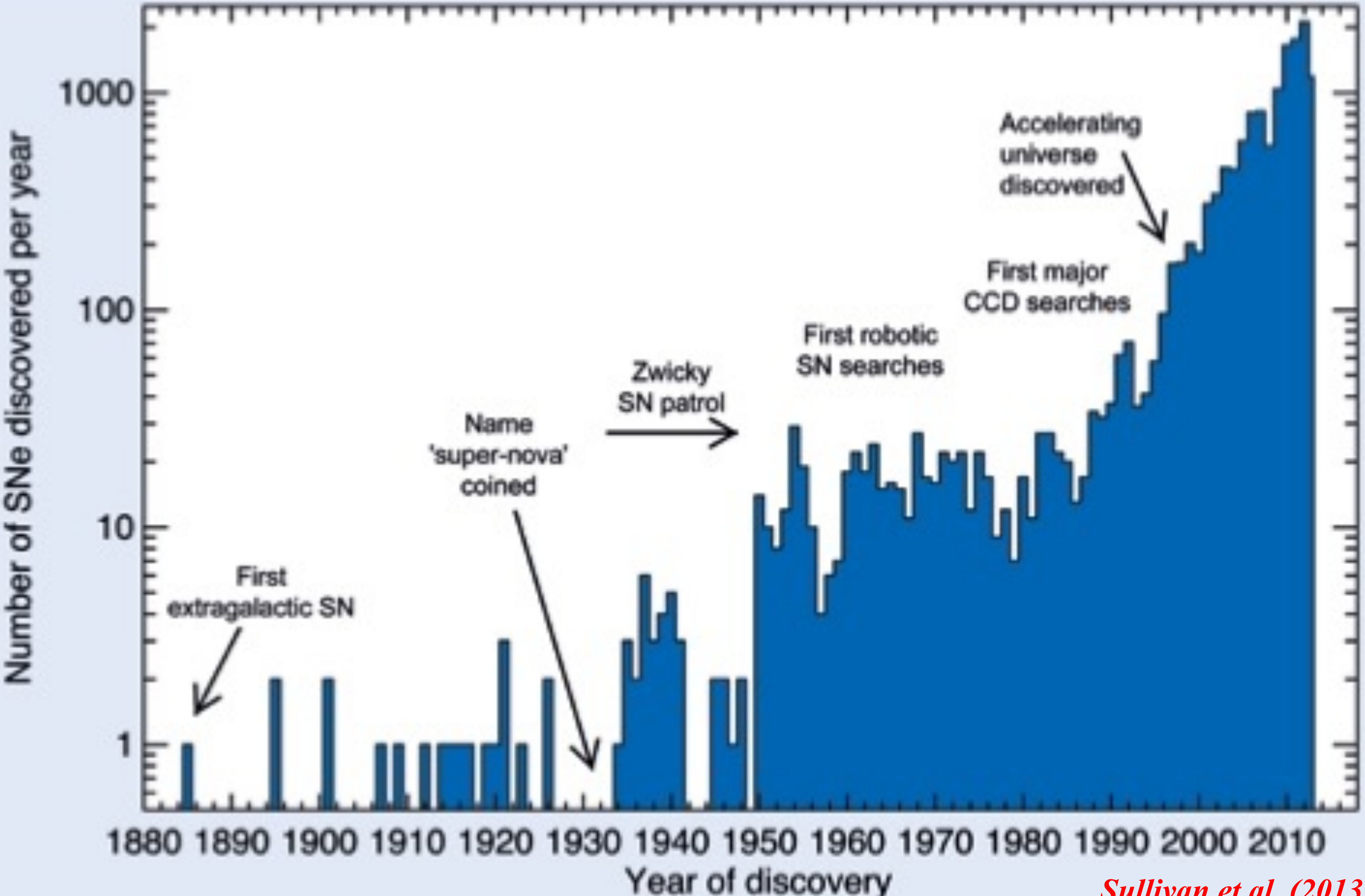
SUNBIRD: workshop on IR bright galaxies and nuclear transients, SAAO, 20th Nov. 2017


2011

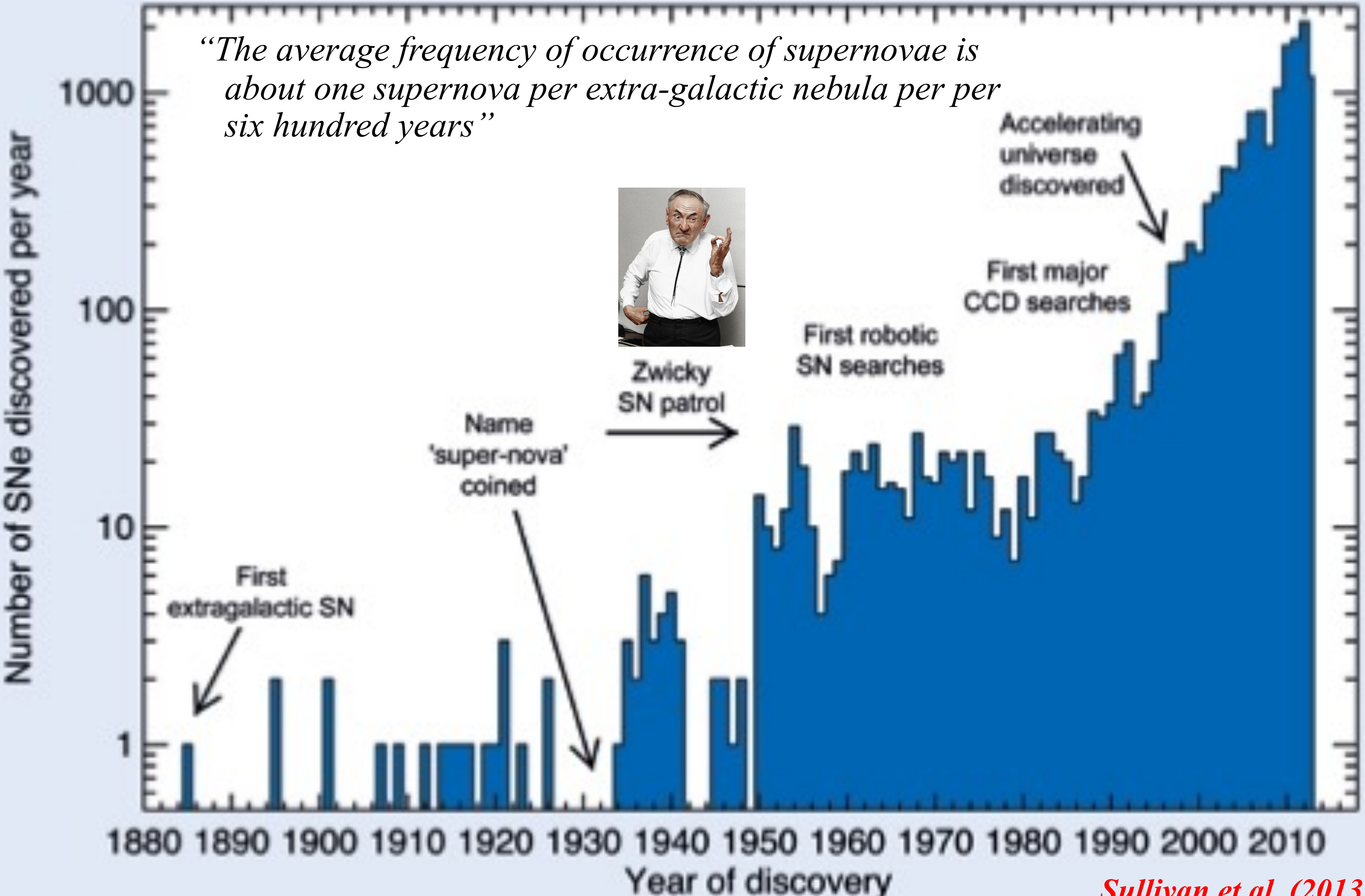

2008


2015

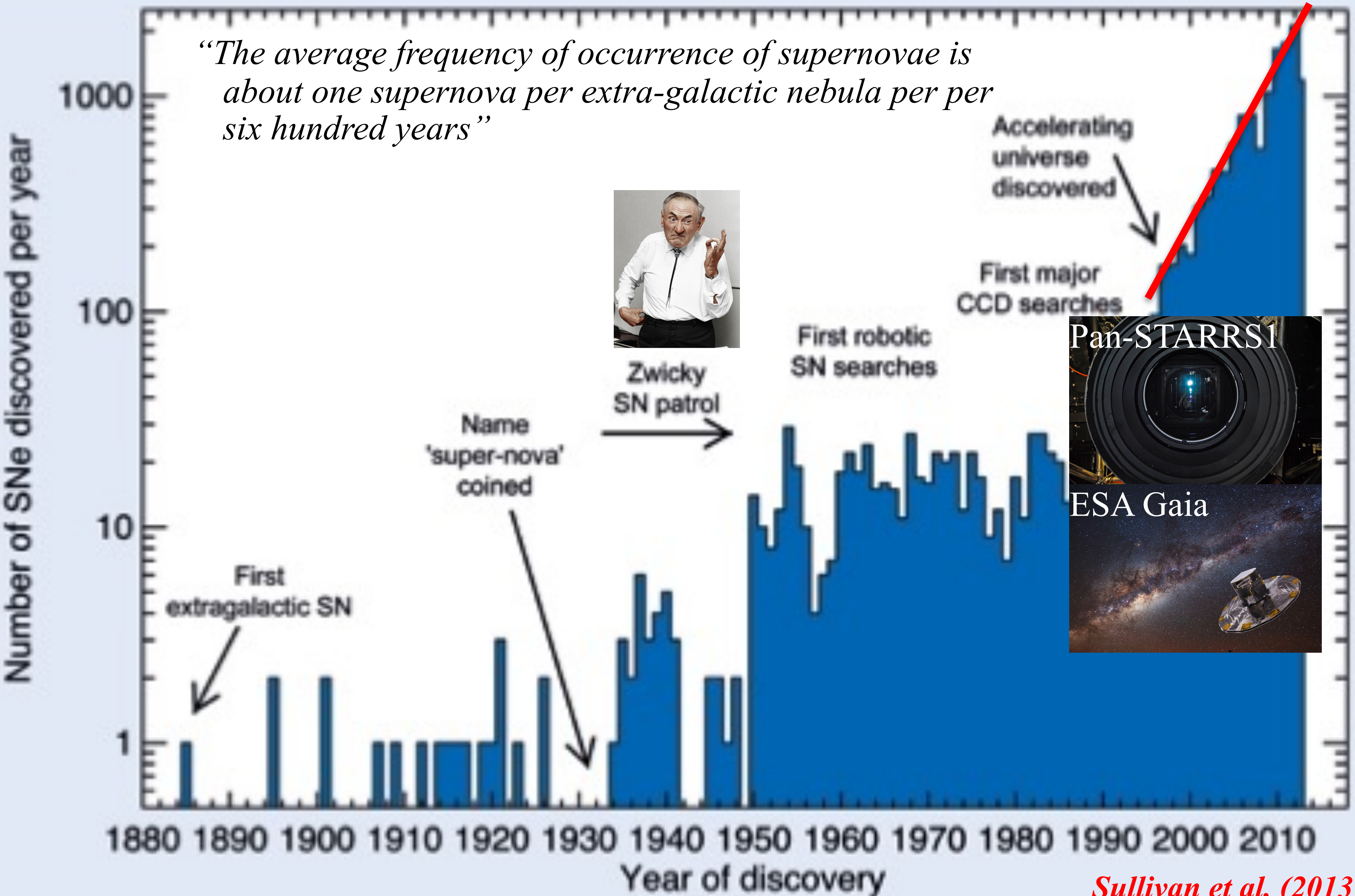

2009
NO FUMAR



Sullivan et al. (2013)



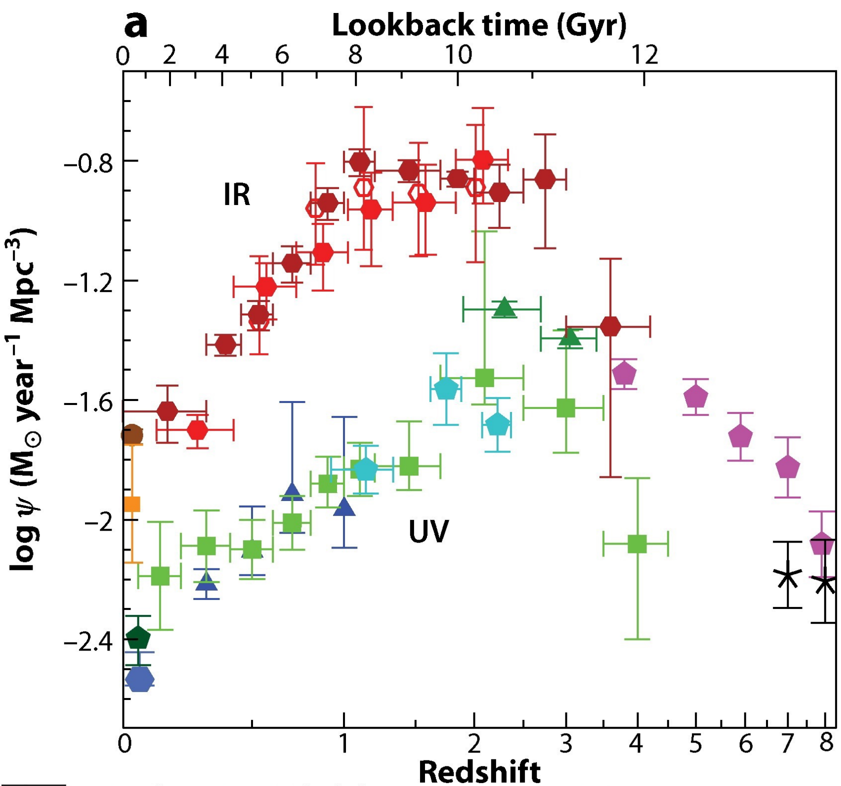
Sullivan et al. (2013)

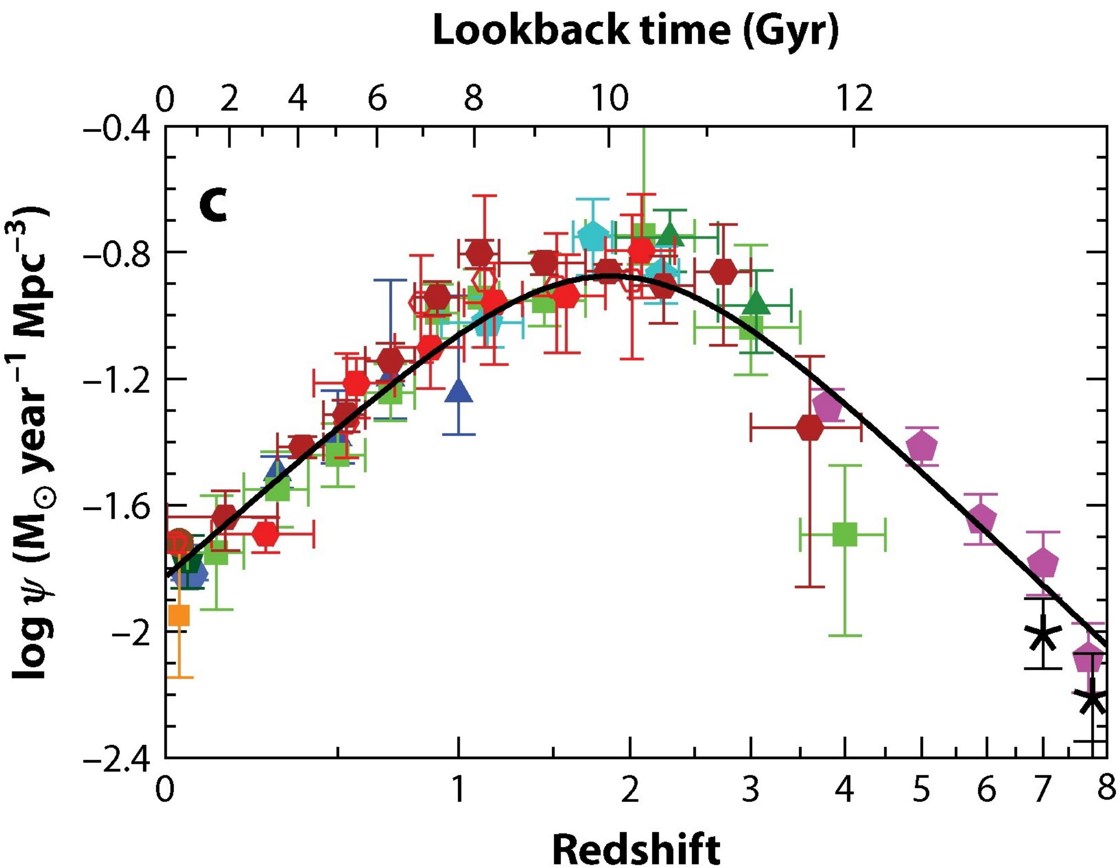


Sullivan et al. (2013)

Cosmic star formation history

- Consistent picture available from UV (e.g. Galex), optical (e.g. HST) and IR (e.g., Spitzer, Herschel, sub-mm) observations up to z ~ 8
- Peaked at z ~ 1.9, declined exponentially at z < 1

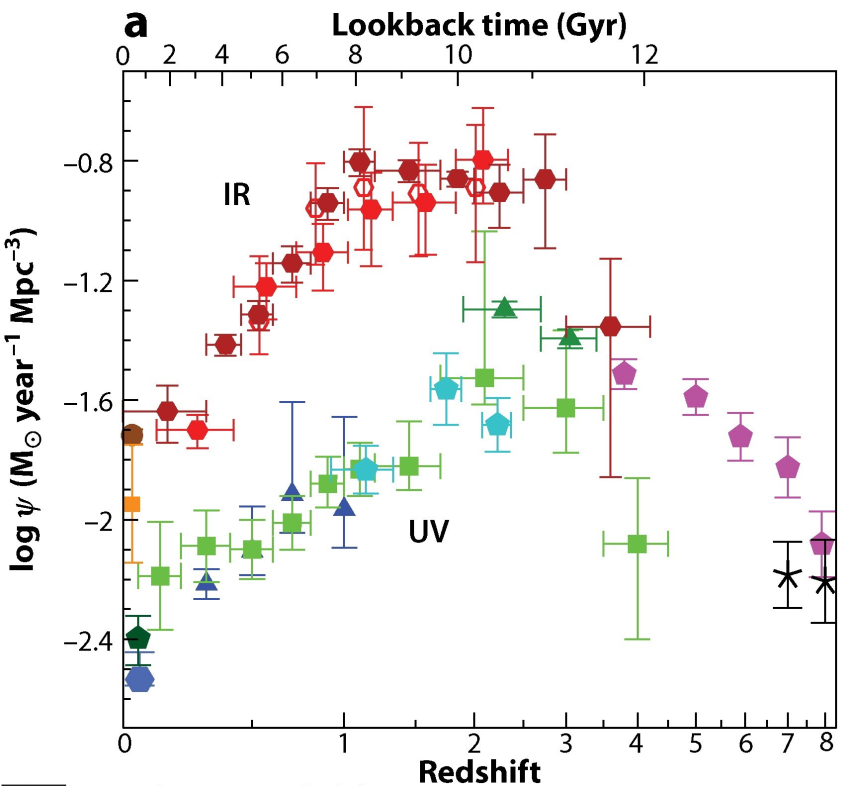


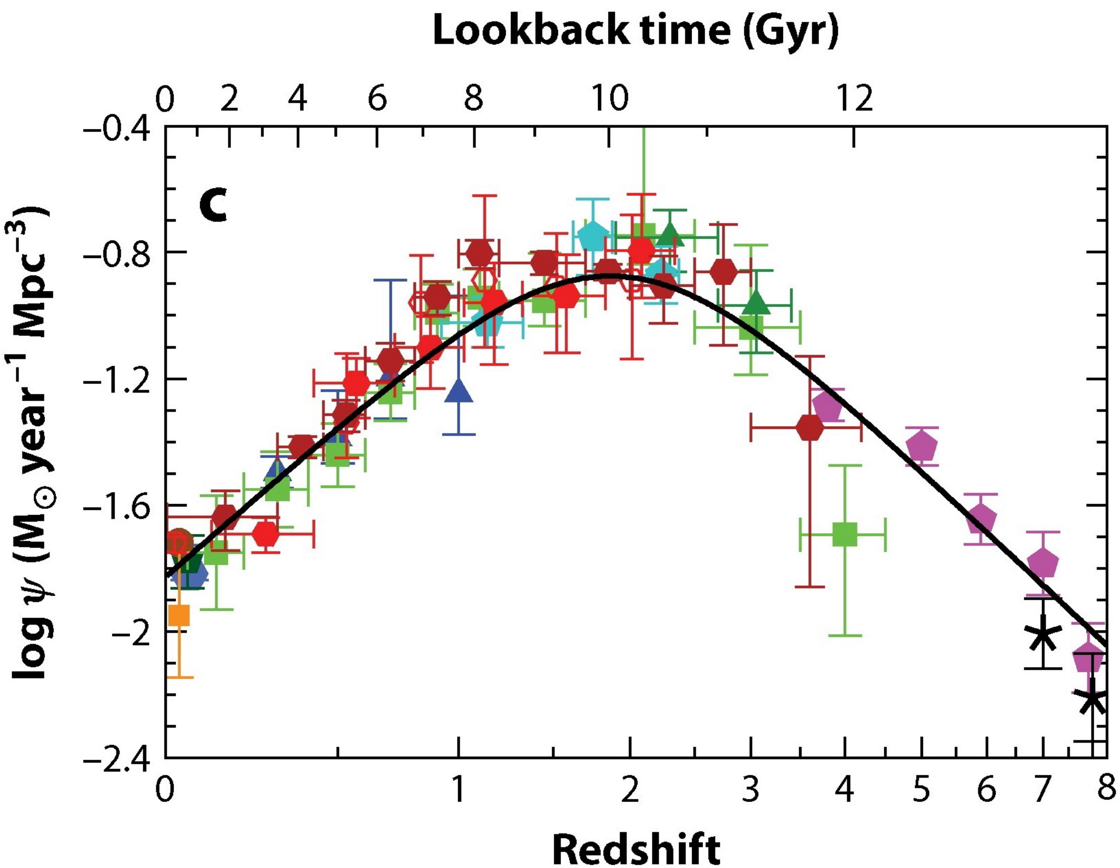


Madau P, Dickinson M. 2014.
Annu. Rev. Astron. Astrophys. 52:415–86

Cosmic star formation history

- Consistent picture available from UV (e.g. Galex), optical (e.g. HST) and IR (e.g., Spitzer, Herschel, sub-mm) observations up to z ~ 8
- Peaked at z ~ 1.9, declined exponentially at z < 1
- One of the most fundamental observables is astrophysical cosmology - a benchmark against which to compare galaxy formation and evolution models





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

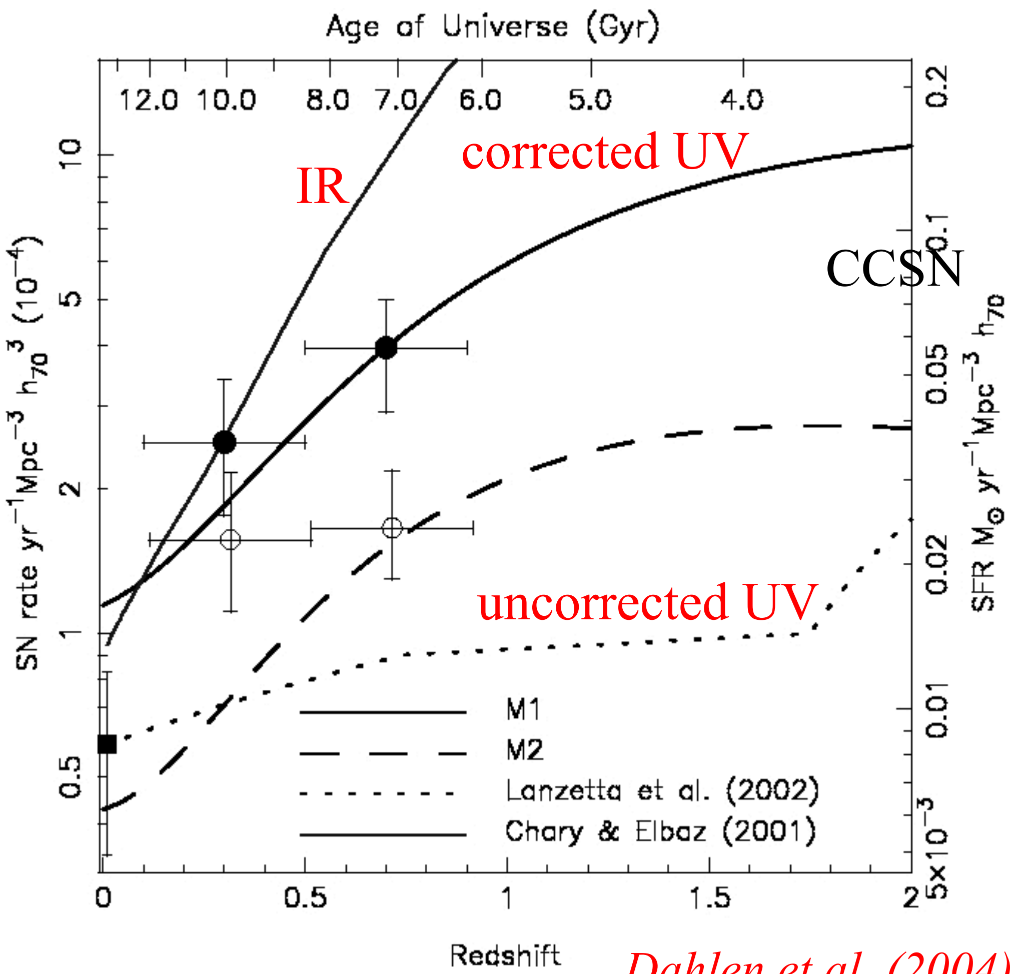
Cosmic star formation history from SN rates

- Core-collapse SNe come from massive stars ($\geq$8 $M_\odot$) with short lifetimes (< ~50 Myr)
- Can assume a direct relation between the core-collapse SN rate and SFR:

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

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

for core-collapse SN progenitors between 8 and 50 $M_\odot$ and the Salpeter IMF



Dahlen et al. (2004)

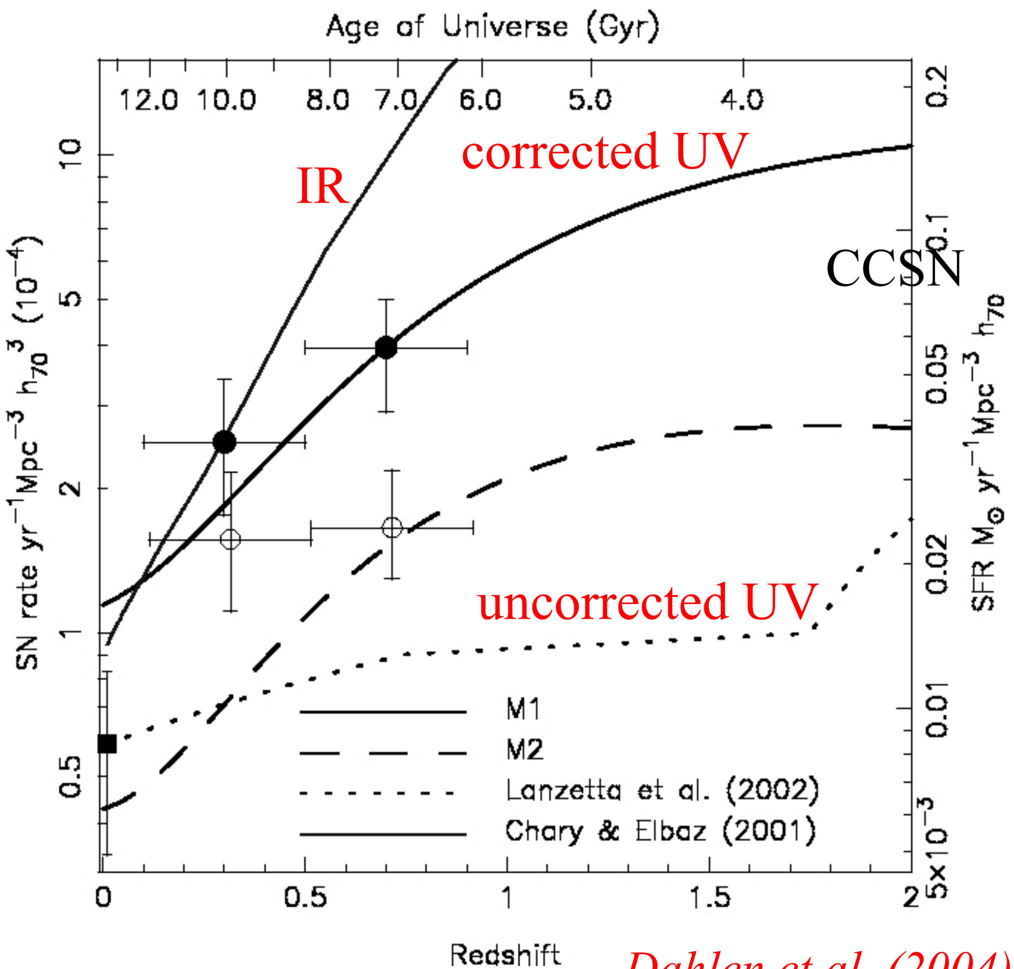
Cosmic star formation history from SN rates

- Core-collapse SNe come from massive stars (≥8 $M_\odot$) with short lifetimes (< ~50 Myr)
- Can assume a direct relation between the core-collapse SN rate and SFR:

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

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

for core-collapse SN progenitors between 8 and 50 $M_\odot$ and the Salpeter IMF

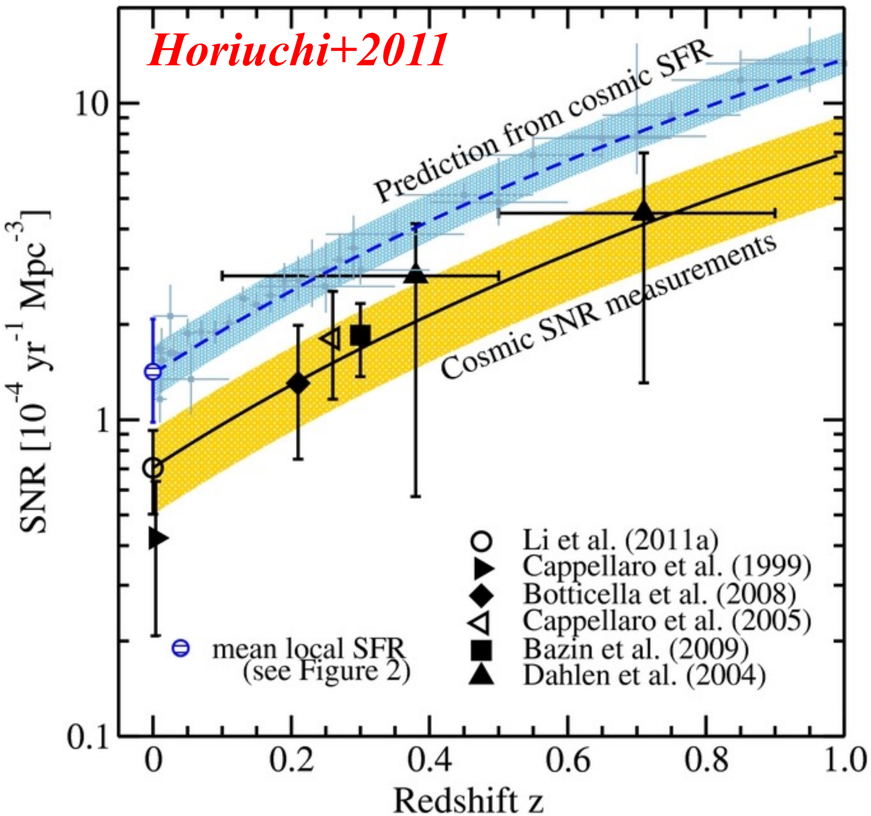


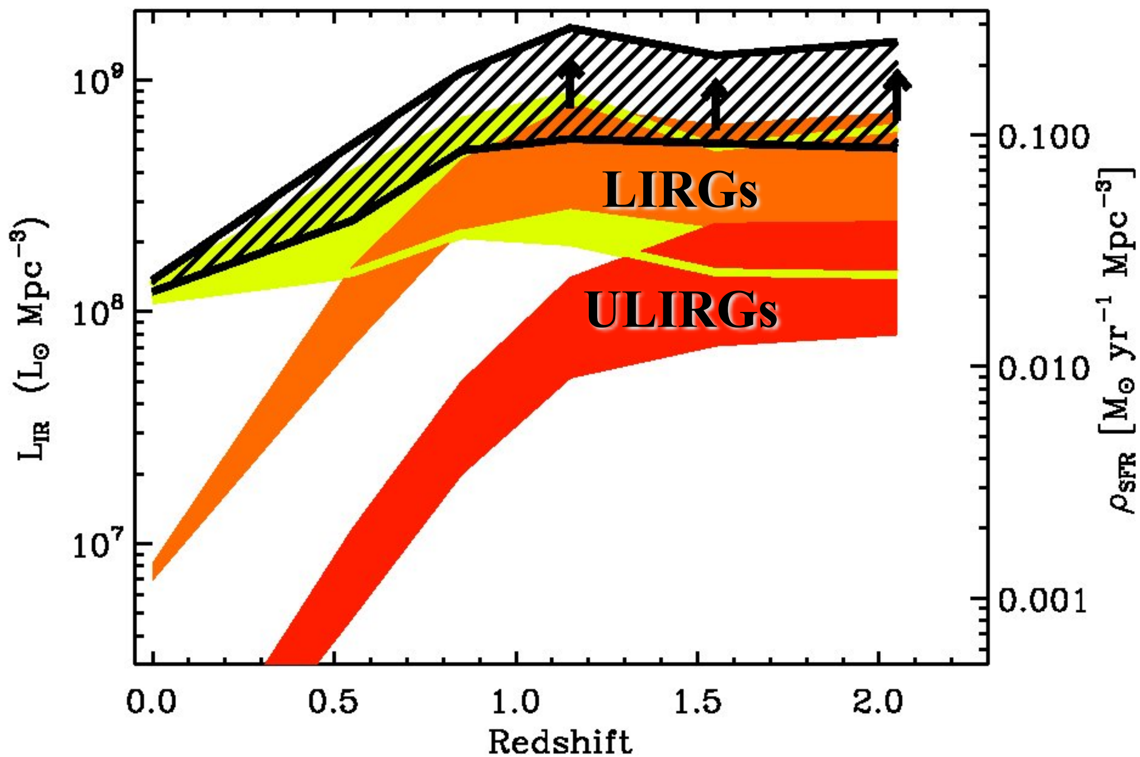
Dahlen et al. (2004)

- SNe can provide an ***independent*** determination of the cosmic star formation rates
- Information on the ***progenitor lower and upper mass cut offs*** for luminous core-collapse SNe

“Dark” SNe in LIRGs and ULIRGs

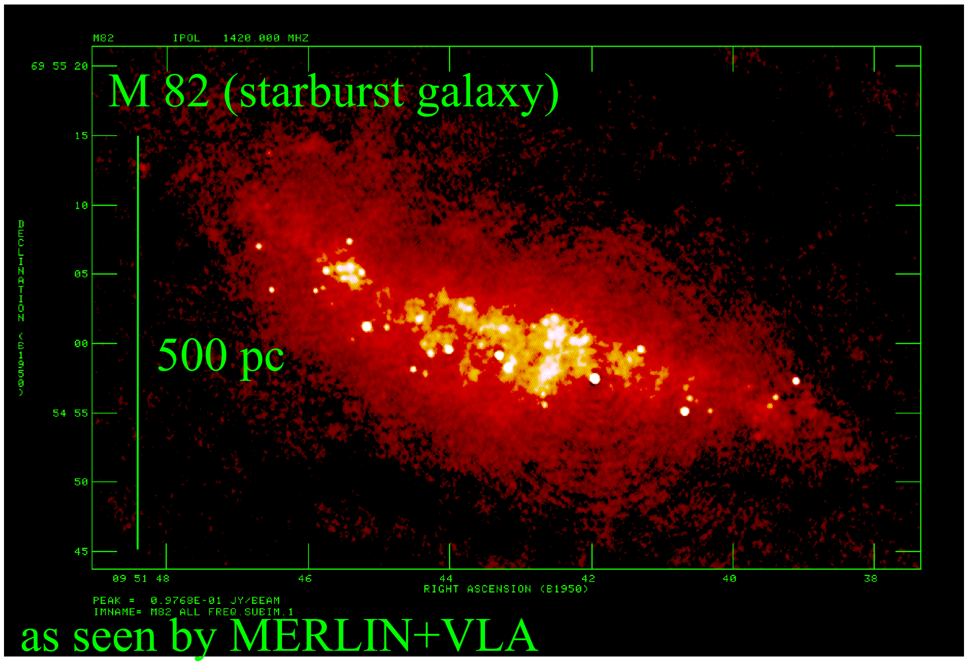
- Are significant numbers of core-collapse SNe ‘missed’ in galaxies even locally?
- (Ultra)luminous IR galaxies locally rare but at z ~1-2 dominate the star formation
- Stars forming rapidly during a few x 100 Myr long starburst episodes, large numbers of massive short lived stars exploding as core-collapse SNe

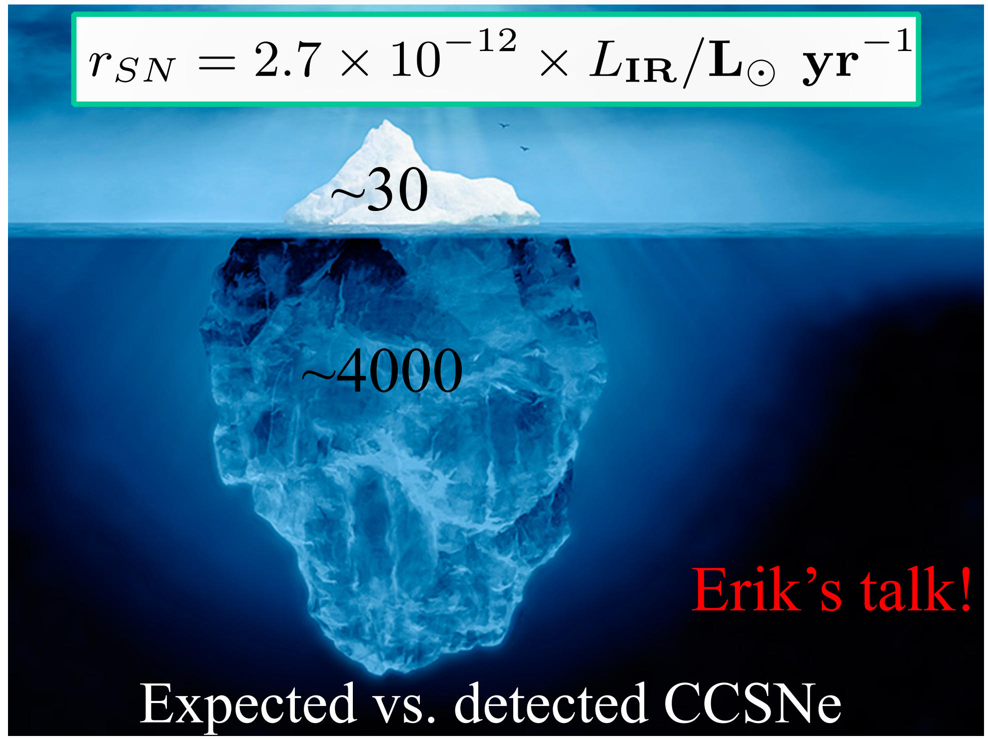




“Dark” SNe in LIRGs and ULIRGs

- Are significant numbers of core-collapse SNe ‘missed’ in galaxies even locally?
- (Ultra)luminous IR galaxies locally rare but at z ~1-2 dominate the star formation
- Stars forming rapidly during a few x 100 Myr long starburst episodes, large numbers of massive short lived stars exploding as core-collapse SNe
- Missed by surveys due to large extinction and concentration to nuclear (1 kpc) regions

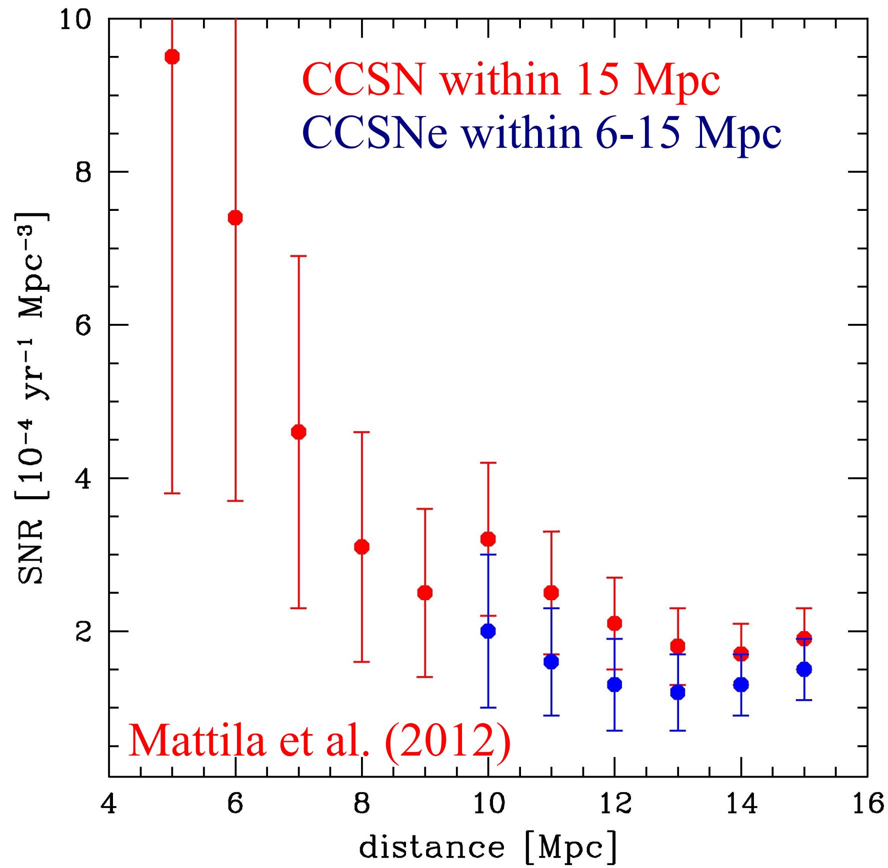




(estimates in *Kool+2017*)

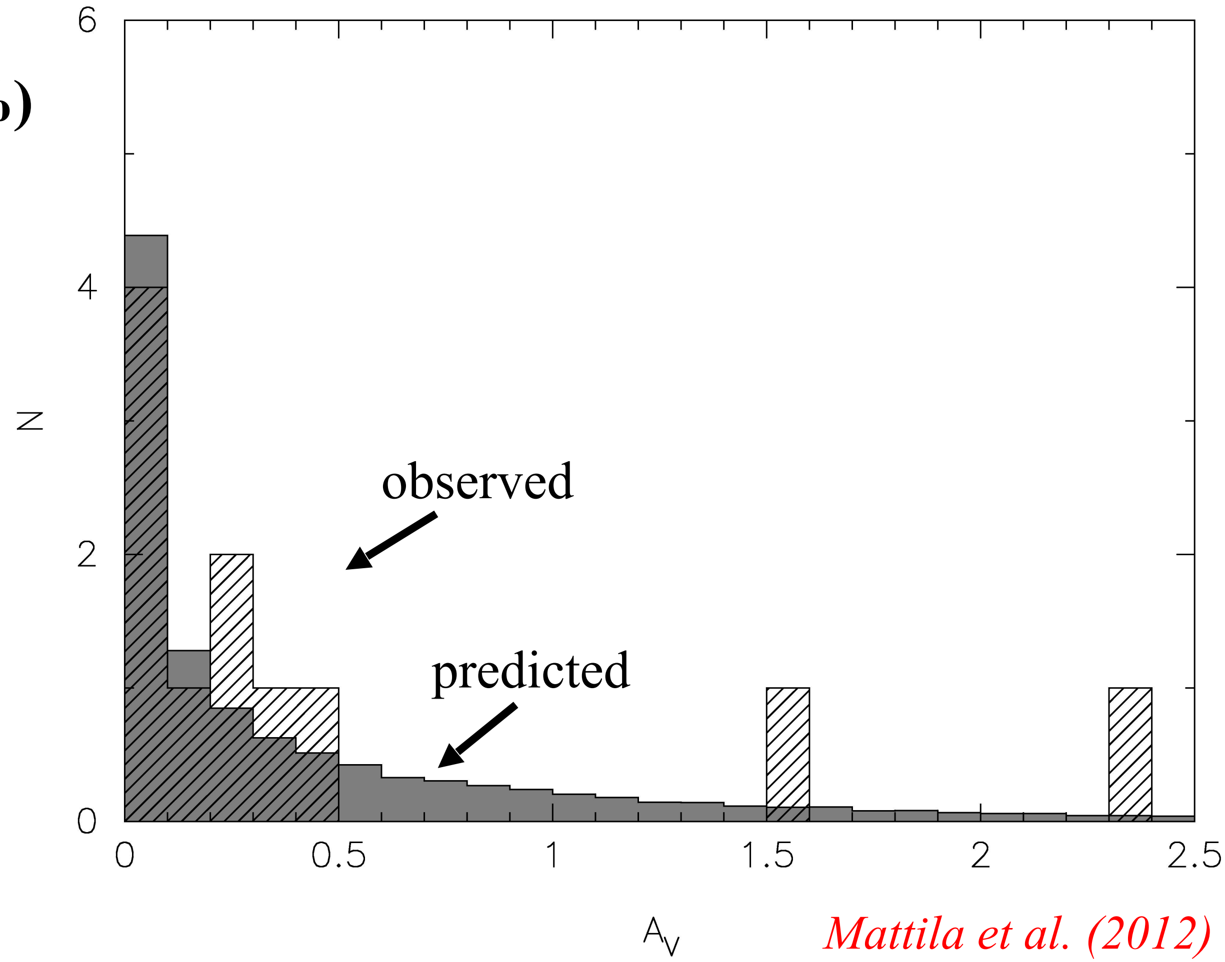
Core-collapse SN rate in the very nearby volume

- Include CCSNe discovered in 2000-2011 within 15 Mpc to avoid missing intrinsically faint or dust obscured events
- Significant excess of SNe within ~6 Mpc caused by local SFR overdensity
- SN rate **$1.5 \pm 0.4 \times 10^{-4}$ SNe yr^{-1} Mpc^{-3}** (between 6-15 Mpc)
- Corresponding SFR **0.021 ± 0.006 $M_\odot$ yr^{-1} Mpc^{-3}** (for Salpeter IMF)
- Consistent with the best fit SFR at z=0 **0.015 $M_\odot$ yr^{-1} Mpc^{-3}** (Madau & Dickinson 2014)



The SN budjet of “normal” galaxies

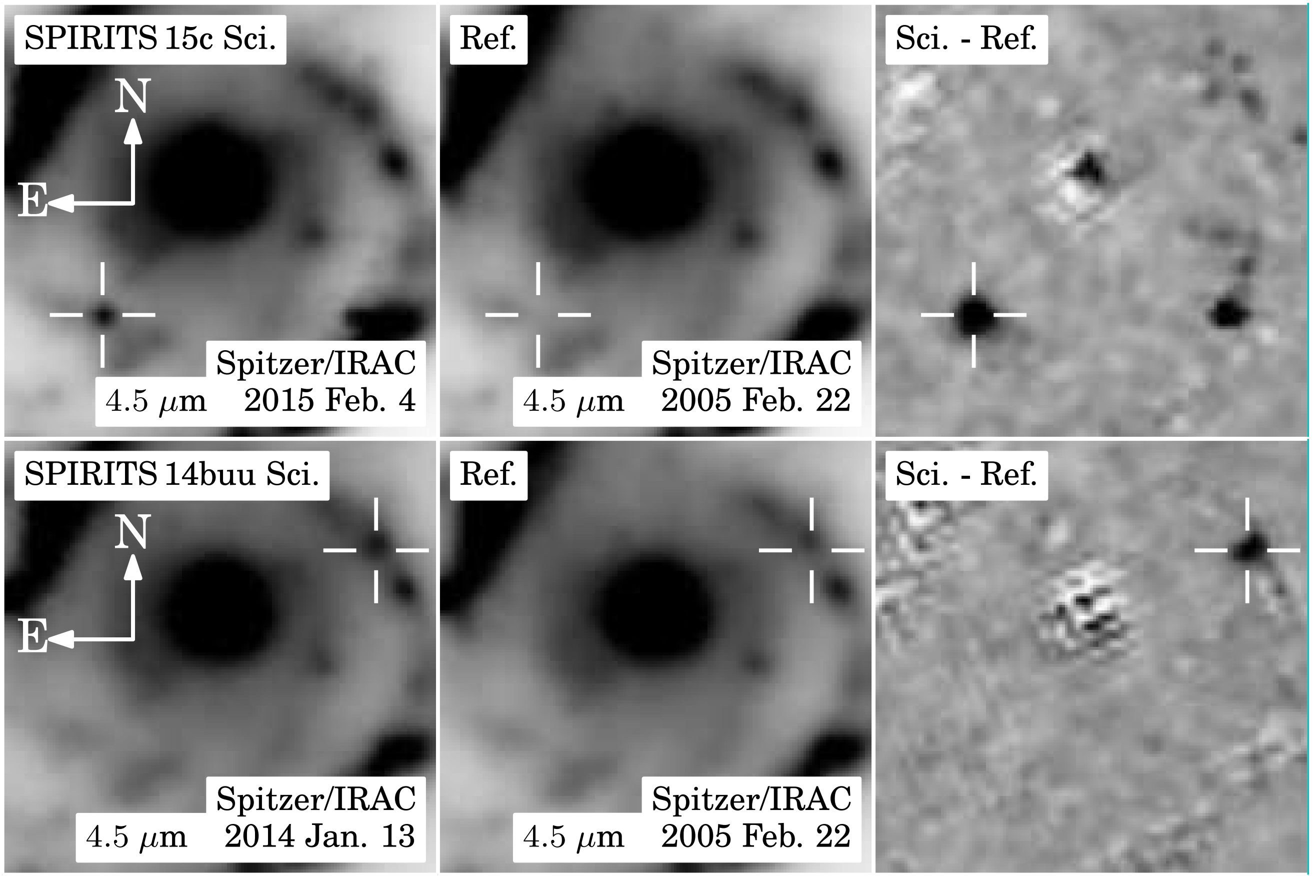
- Concentrate on 13 SNe within 12 Mpc with host galaxy i < 60
- Compare with predictions from a MC simulations (Riello & Patat 2005; Kankare et al. in prep.)
- 2/13 have $A_B > 5$ (expect ~0.3%)
- Missing SN fraction: **15% (5-36%)**



Mattila et al. (2012)

Spitzer InfraRed Intensive Transients Survey

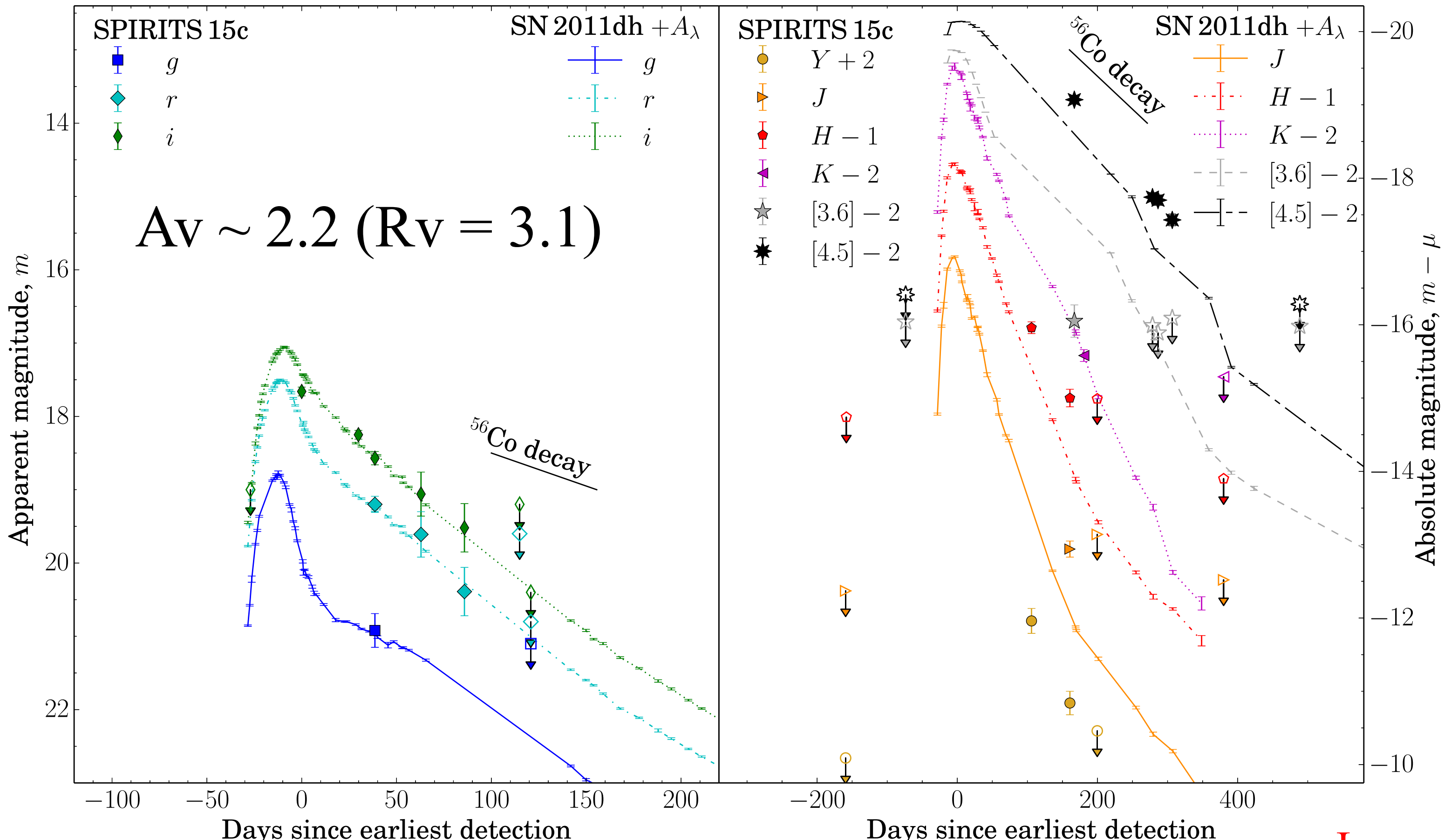
- 3-yr survey of 194 galaxies within 20 Mpc with Spitzer/IRAC at 3.6 and 4.5 μm
- First year with monthly cadence, then weekly cadence down to 20 mag at 3.6 μm
- 300 hours / Spitzer cycle (PI: Mansi Kasliwal)



Jencson et al. (2017)

Spitzer InfraRed Intensive Transients Survey

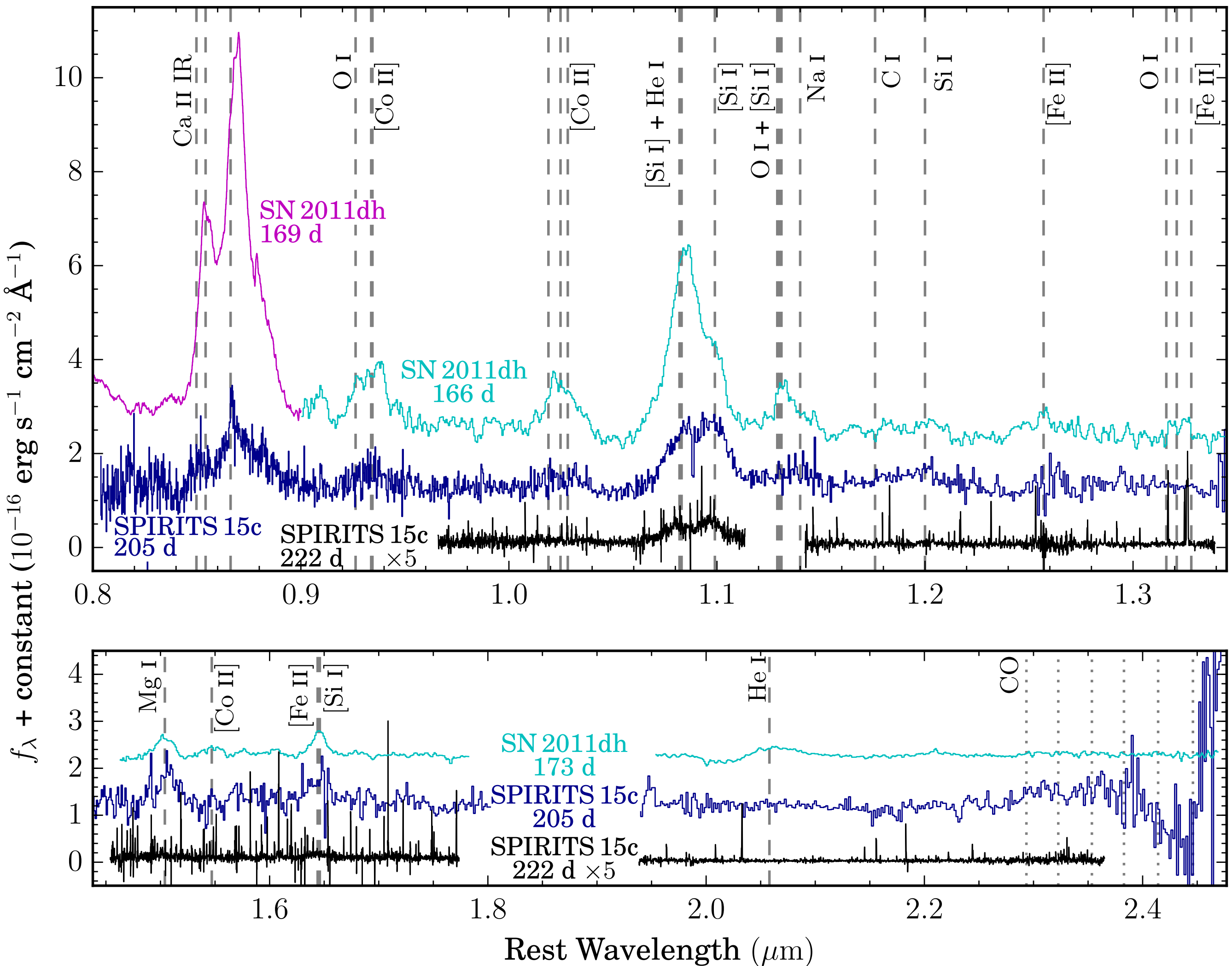
- 3-yr survey of 194 galaxies within 20 Mpc with Spitzer/IRAC at 3.6 and 4.5 μm
- First year with monthly cadence, then weekly cadence down to 20 mag at 3.6 μm
- 300 hours / Spitzer cycle (PI: Mansi Kasliwal)



Jencson et al. (2017)

Spitzer InfraRed Intensive Transients Survey

- 3-yr survey of 194 galaxies within 20 Mpc with Spitzer/IRAC at 3.6 and 4.5 μm
- First year with monthly cadence, then weekly cadence down to 20 mag at 3.6 μm
- 300 hours /

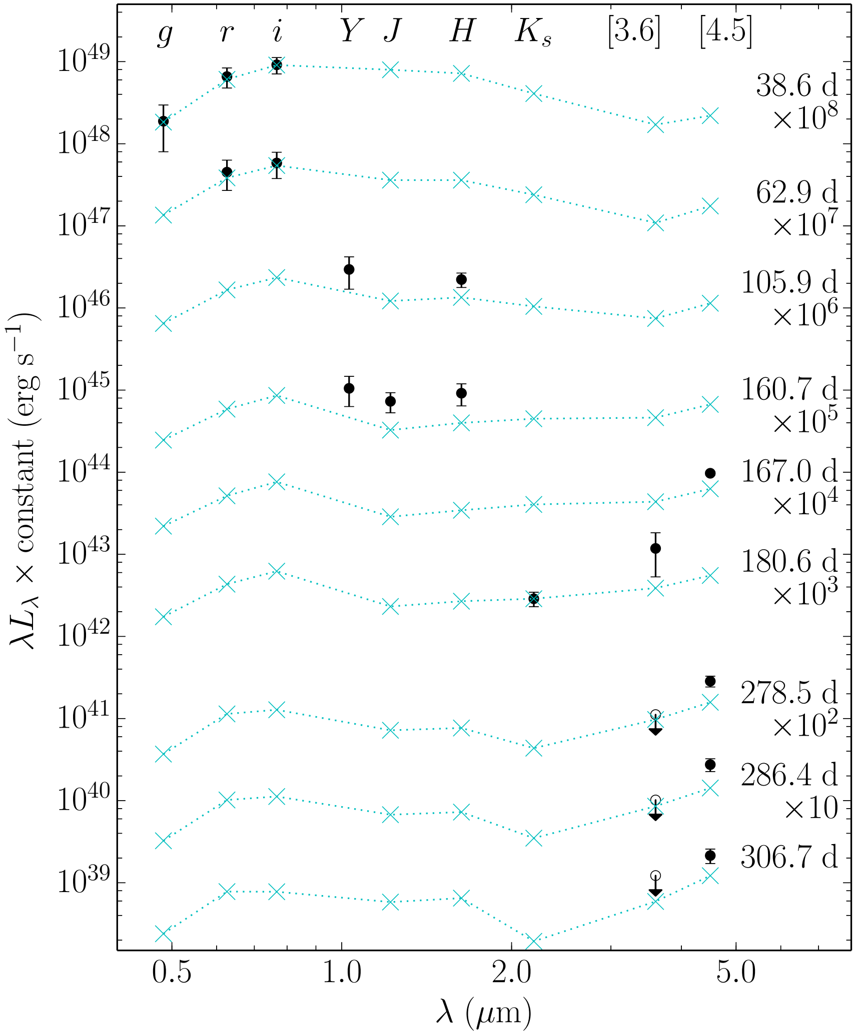


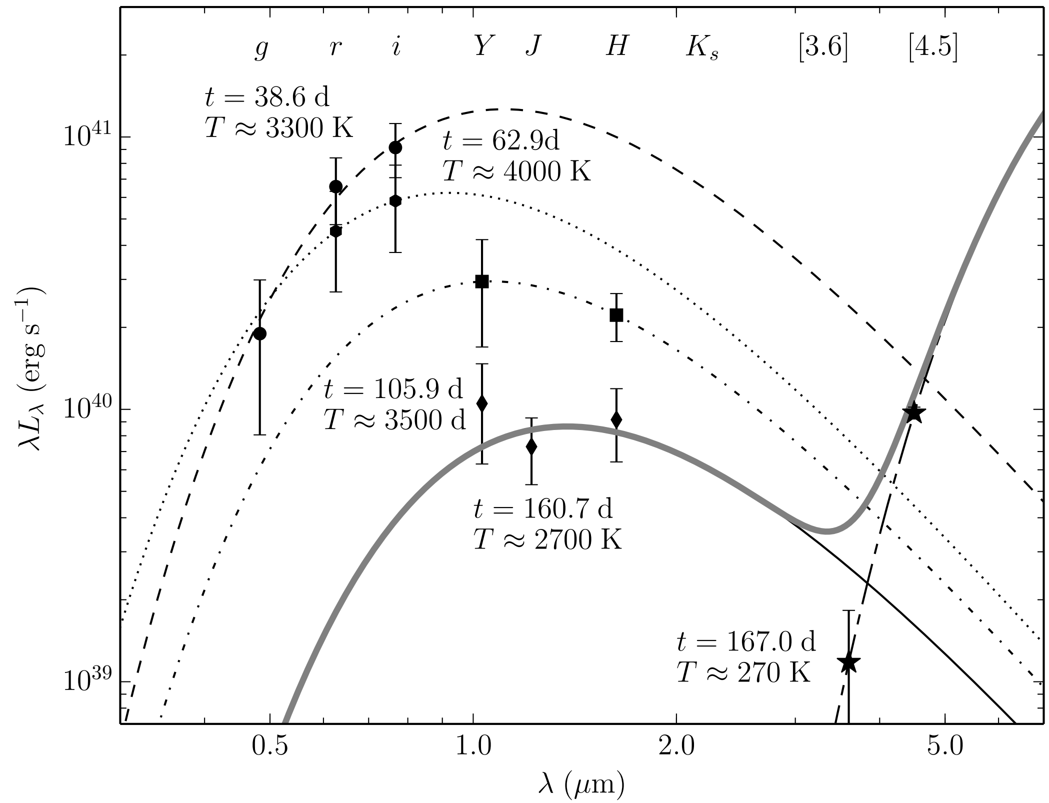
Jencson et al. (2017)

Spitzer InfraRed Intensive Transients Survey

- 3-yr survey of 194 galaxies within 20 Mpc with Spitzer/IRAC at 3.6 and 4.5 μm
- First year with monthly cadence, then weekly cadence down to 20 mag at 3.6 μm

si Kasliwal)





Jencson et al. (2017)

Spitzer InfraRed Intensive Transients Survey

- 3-yr survey of 194 galaxies within 20 Mpc with Spitzer/IRAC at 3.6 and 4.5 μm
- First year with monthly cadence, then weekly cadence down to 20 mag at 3.6 μm
- 300 hours / Spitzer cycle (PI: Mansi Kasliwal)
- Spitzer discovery of two obscured SNe; in addition 9 optically discovered CCSNe
  - Suggest a missing fraction of 2/11 ~ 18%
  - More recently more Spitzer discoveries suggesting up to 50% missing fraction (Jakob Jencson @ Dynamic IR sky workshop, Caltech)

Jencson et al. (2017)

THE ASTROPHYSICAL JOURNAL, 336:L67–L70, 1989 January 15

INFRARED SUPERNOVAE IN STARBURSTS

DAVE VAN BUREN[1] AND COLIN A. NORMAN
Department of Physics and Astronomy, The Johns Hopkins University; and Space Telescope Science Institute
Received 1988 June 17; accepted 1988 October 20

ABSTRACT

We consider the problem of uniquely confirming that the luminosity source of starburst galaxies is a young population of massive stars. Unambiguous detection of the supernova explosions associated with a massive stellar population would provide proof of the starburst hypothesis. High spatial resolution narrow-band infrared imaging of starburst galaxies directly detects the cobalt synthesized in Type II supernova explosions. Coupled with observations of other infrared lines and continuum, progenitor masses can be at least roughly estimated. A statistically large sample of starburst supernovae will lead to an average starburst initial mass function. Standard candles can also be constructed, based on both individual and populations of supernovae. With current and planned instruments, *K*-band supernovae can be found out to cosmological distances.

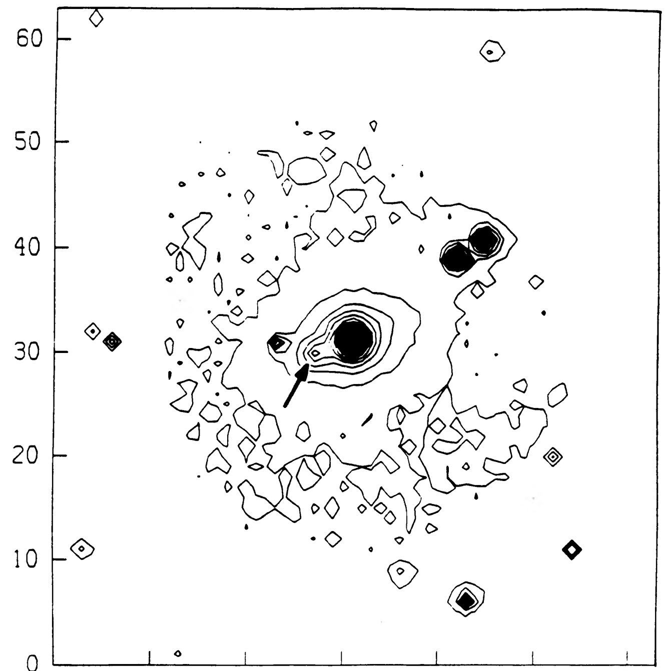


FIG. 2.—Simulation of a 1 hr *K*-band detection experiment on a 4 m using a good present-day detector. The starburst has a luminosity of $10^{11}\ L_{\odot}$ and is 50 Mpc distant. The image corresponds to near maximum light of the supernova (*arrow*) which suffers 2.5 mag of *K*-band extinction. Contour intervals are 5 σ; axes are pixel numbers (each pixel = 0″.35).

THE ASTROPHYSICAL JOURNAL, 336:L67–L70, 1989 January 15

INFRARED SUPERNOVAE IN STARBURSTS

DAVE VAN BUREN[1] AND COLIN A. NORMAN
Department of Physics and Astronomy, The Johns Hopkins University; and Space Telescope Science Institute
Received 1988 June 17; accepted 1988 October 20

ABSTRACT

We consider the problem of uniquely confirming that the luminosity source of starburst galaxies is a young population of massive stars. Unambiguous detection of the supernova explosions associated with a massive stellar population would provide proof of the starburst hypothesis. High spatial resolution narrow-band infrared imaging of starburst galaxies directly detects the cobalt synthesized in Type II supernova explosions. Coupled with observations of other infrared lines and continuum, progenitor masses can be at least roughly estimated. A statistically large sample of starburst supernovae will lead to an average starburst initial mass function. Standard candles can also be constructed, based on both individual and populations of supernovae. With current and planned instruments, K-band supernovae can be found out to cosmological distances.

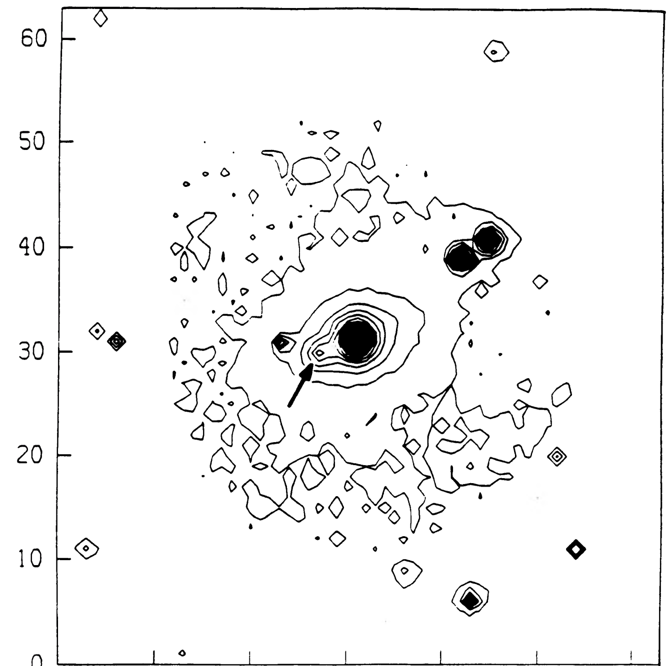


FIG. 2.—Simulation of a 1 hr K-band detection experiment on a 4 m using a good present-day detector. The starburst has a luminosity of $10^{11}\ L_\odot$ and is 50 Mpc distant. The image corresponds to near maximum light of the supernova (*arrow*) which suffers 2.5 mag of K-band extinction. Contour intervals are 5 σ; axes are pixel numbers (each pixel = 0.35).

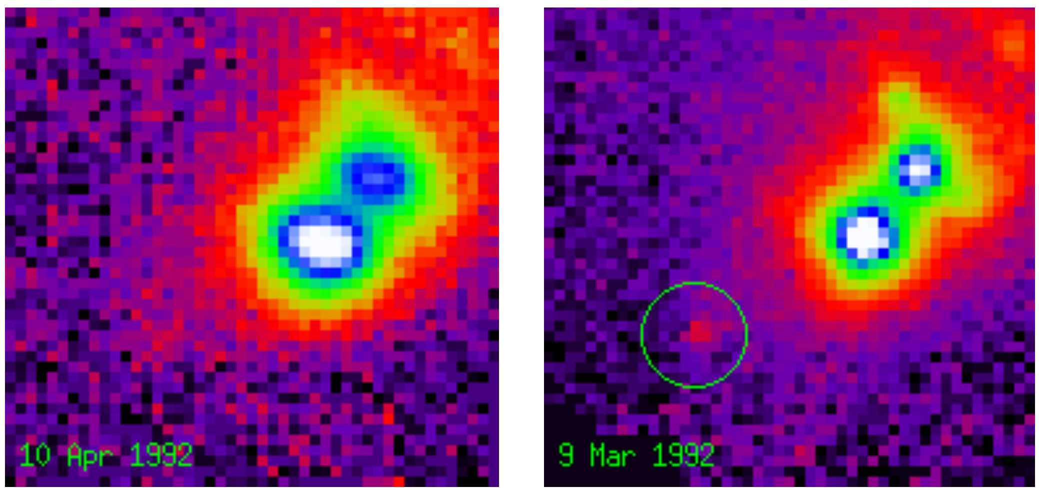
Circular No. 5960

Central Bureau for Astronomical Telegrams
INTERNATIONAL ASTRONOMICAL UNION

SUPERNOVA 1992bu IN NGC 3690

D. Van Buren, T. Jarrett, S. Terebey, and C. Beichman, Infrared Processing and Analysis Center, California Institute of Technology and Jet Propulsion Laboratory; and M. Shure and C. Kaminski, NASA Infrared Telescope Facility, Institute for Astronomy, University of Hawaii, report their discovery of an apparent supernova in NGC 3690 (= Markarian 171) at R.A. = 11h25m42s.0, Decl. = +58o50'10" (equinox 1950.0) ~~on archival images taken in the K (2.2 micron)~~ band as part of a search for supernovae in starburst galaxies. Offsets from Core B1 ~~(cf. Wynn Williams et al. 1991, Ap.J. 377, 426)~~ of the galaxy are 5" east ~~and 3" south.~~ The object appears in ProtoCam data (obtained at the IRTF, Mauna Kea) for 1992 Mar. 9 UT (when K = 16.6 +/- 0.2), Apr. 10 ~~(17.2 +/- 0.3)~~, and May 6 (18.1 +/- 0.5). It does not appear to limiting magnitude K about 19 in NSFCam IRTF images from 1993 Dec. 27.

$M_K \sim -16.7$
0.02 mag / day

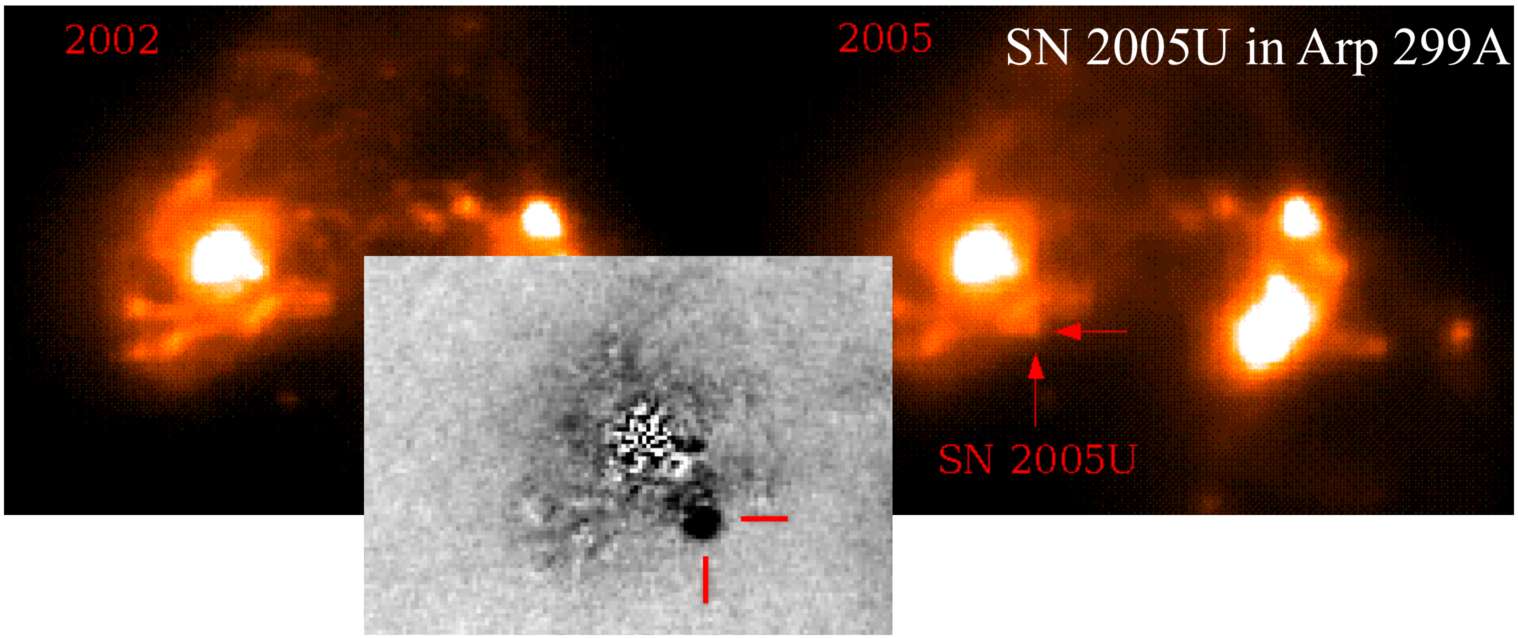


SN 1992bu in Arp 299B

(www.ipac.caltech.edu/ipac/info/sn1992/sn1992_NGC3690.html)

Seeing-limited near-IR searches

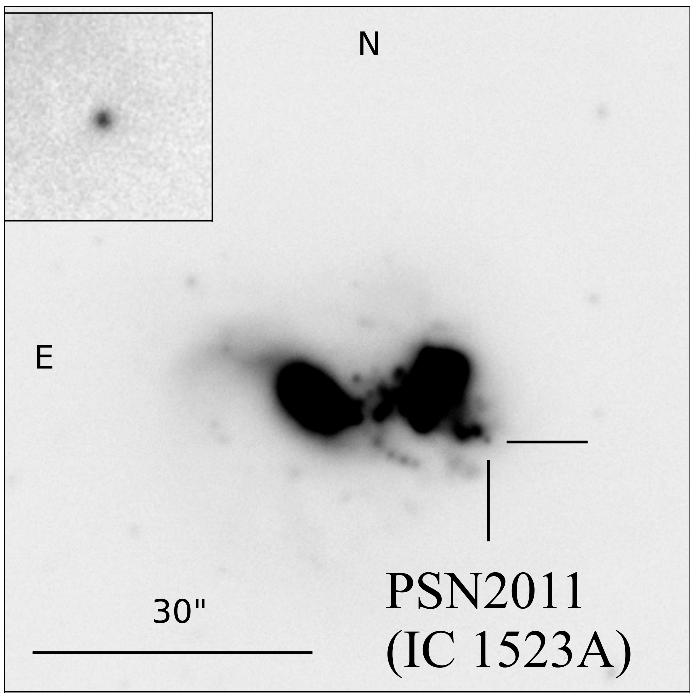
- In the near-IR ($A_K \sim 0.1\ A_V$) extinction strongly reduced compared to optical observations
- A number of K-band searches carried-out in starbursts and U/LIRGs under natural seeing:
  - 40 starburst galaxies within 45 Mpc with WHT in 2001-2005 (Mattila+)
  - 40 LIRGs within 300 Mpc with NTT & TNG in 1999-2001 (Maiolino+02; Mannucci+03)
  - 30 LIRGs within 200 Mpc with VLT/HAWK-I in 2010-2011 (Miluzio+2013)

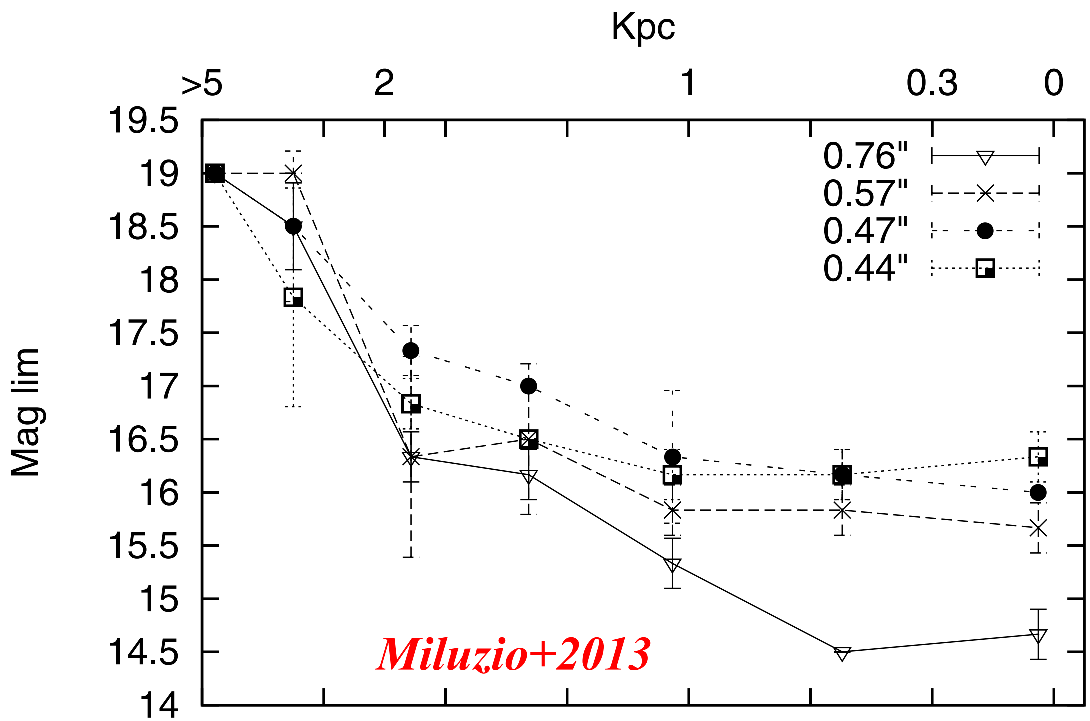


Mattila+2001,2004,2005

Seeing-limited near-IR searches

- In the near-IR ($A_K \sim 0.1\ A_V$) extinction strongly reduced compared to optical observations
- A number of K-band searches carried-out in starbursts and U/LIRGs under natural seeing:
  - 40 starburst galaxies within 45 Mpc with WHT in 2001-2005 (Mattila+)
  - 40 LIRGs within 300 Mpc with NTT & TNG in 1999-2001 (Maiolino+02; Mannucci+03)
  - 30 LIRGs within 200 Mpc with VLT/HAWK-I in 2010-2011 (Miluzio+2013)

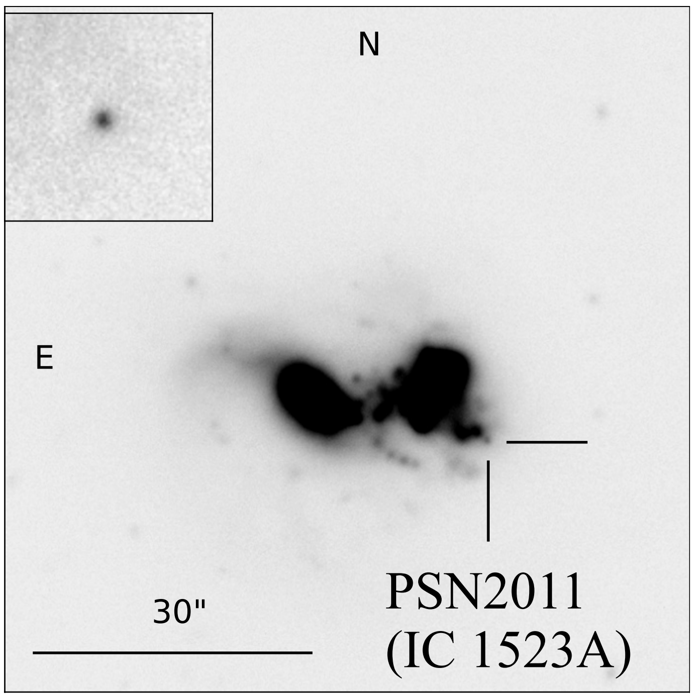


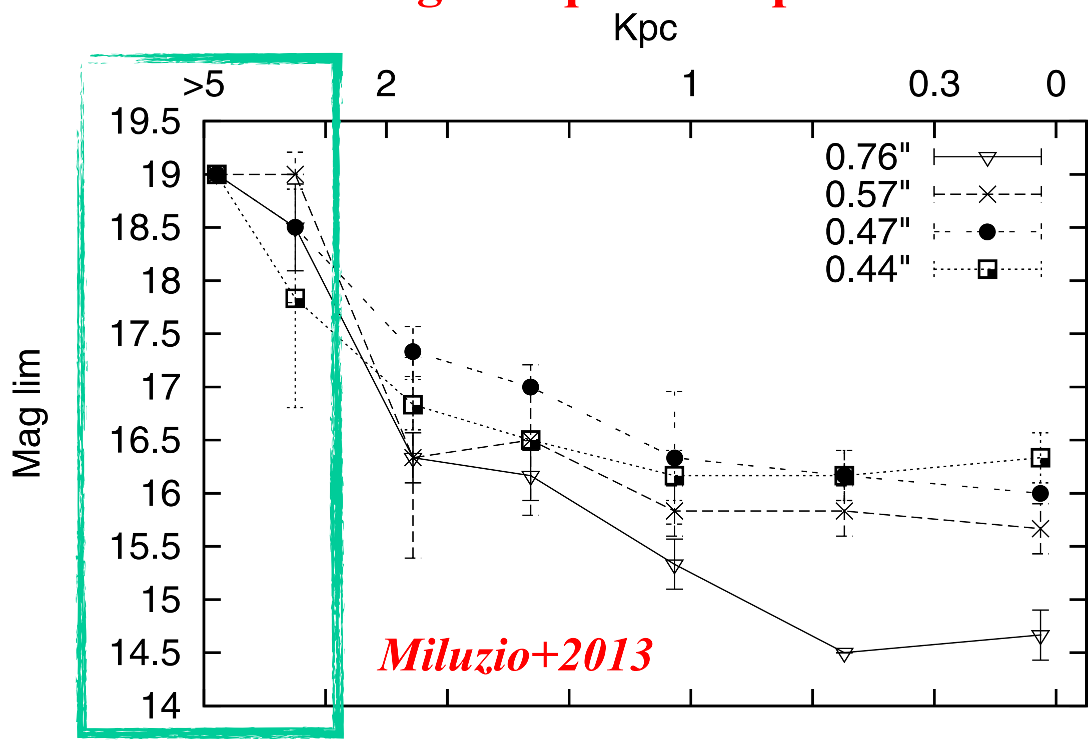


Seeing-limited near-IR searches

- In the near-IR ($A_K \sim 0.1\ A_V$) extinction strongly reduced compared to optical observations
- A number of K-band searches carried-out in starbursts and U/LIRGs under natural seeing:
  - 40 starburst galaxies within 45 Mpc with WHT in 2001-2005 (Mattila+)
  - 40 LIRGs within 300 Mpc with NTT & TNG in 1999-2001 (Maiolino+02; Mannucci+03)
  - 30 LIRGs within 200 Mpc with VLT/HAWK-I in 2010-2011 (Miluzio+2013)

Handful of SNe recovered but mostly outside the IR bright and heavily obscured nuclear regions; higher spatial resolution at near-IR wavelength required to probe these regions

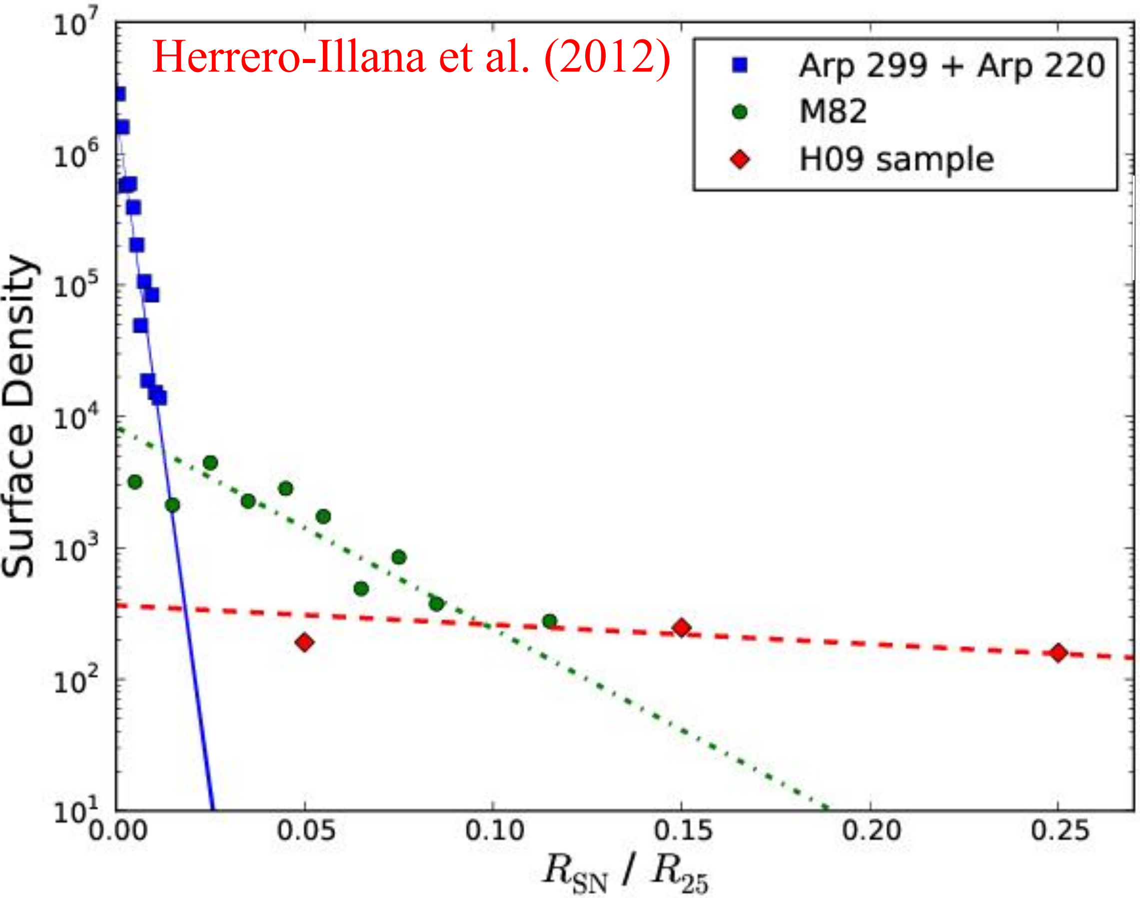


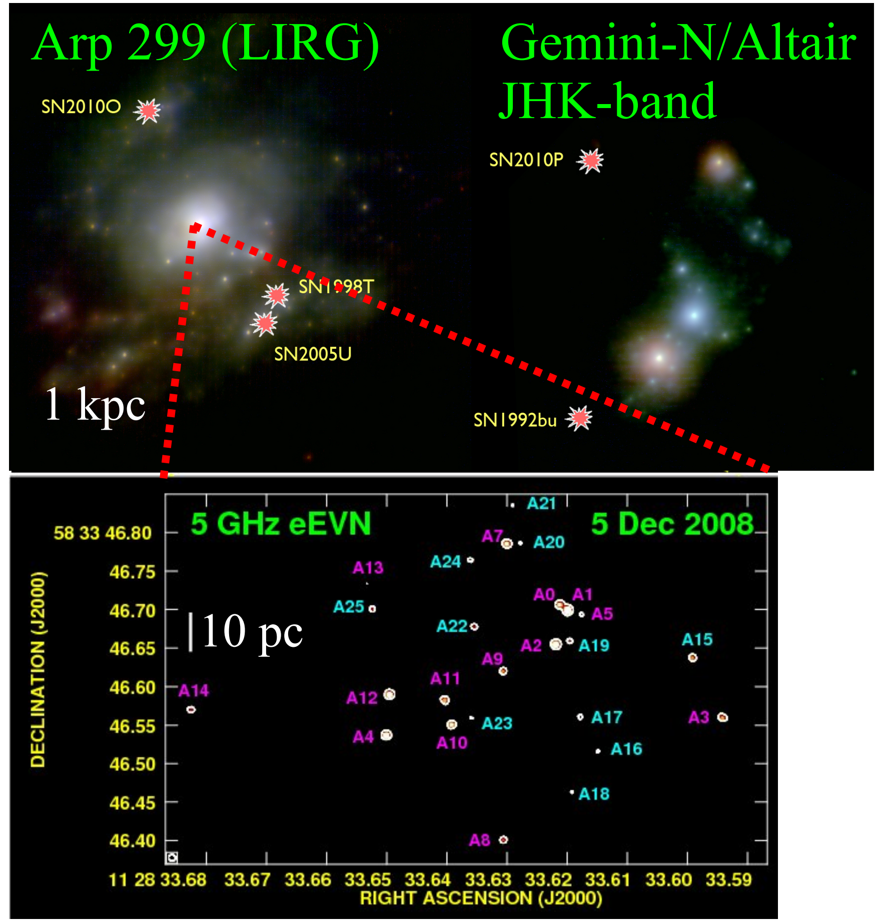


Correction for the "dark" SNe in U/LIRGs

High spatial resolution in the IR or radio required for the detection and study of SNe within the nuclear regions of galaxies

Miguel's talk !



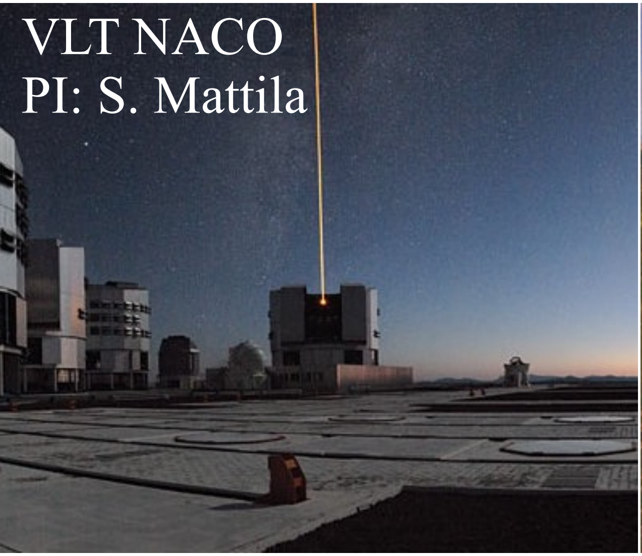


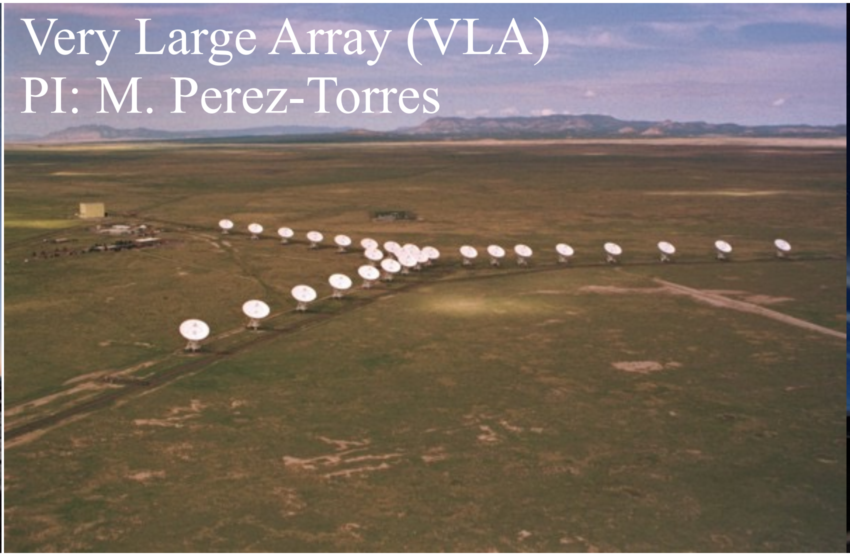
Perez-Torres et al. (2009)

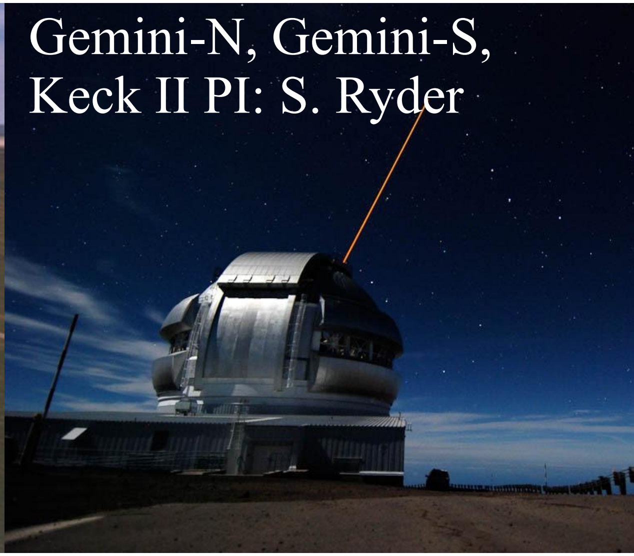
High resolution (AO) near-IR searches in LIRGs

- Use AO to provide ~0.1” resolution in the near-IR *K*-band for the SN detection and study
- Observe the most promising LIRGs within ~120 Mpc (0.1” corresponds to <60pc)
    - ESO VLT + NACO (AO with NGS)
    - Gemini-N + ALTAIR/NIRI (AO with LGS)
    - Gemini-S + GeMS/GSAOI (MCAO with LGSs)
    - Keck II + NIRC2 (AO with LGSs)

Talks by Tom, Erik, Miguel !



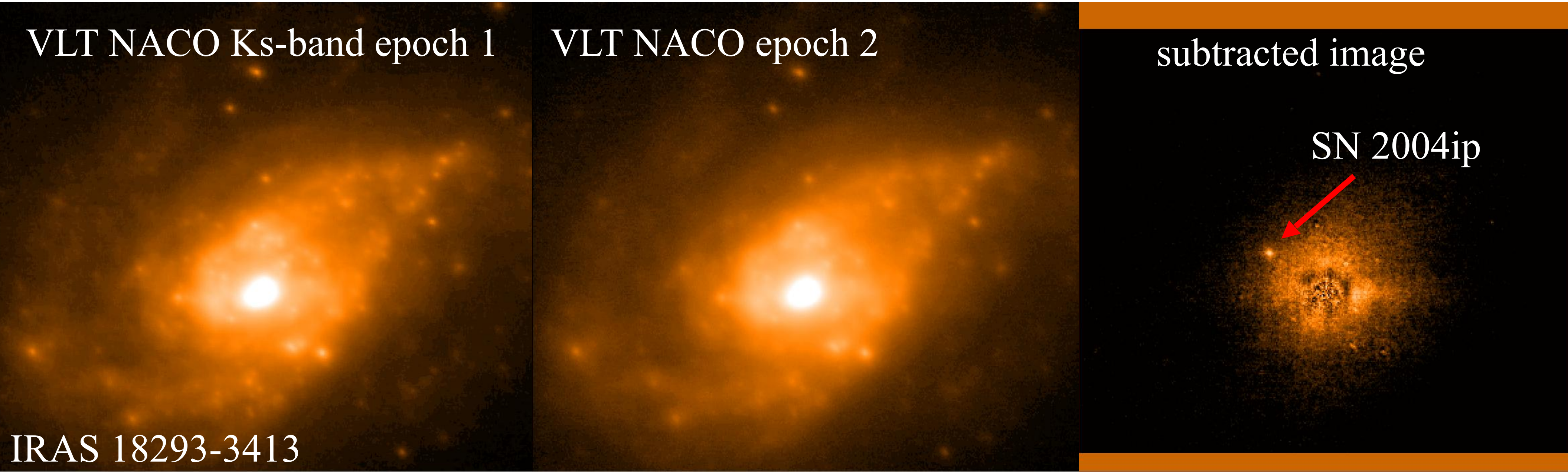




Mattila+2007, 2012; Kankare,SM+2008,2012,2014; Perez-Torres+2007; Ryder+2014; Herrero-Illana+17; Romero-Canizales+2011,2012,2014; Väisänen+2008a,b; Randriamanakoto+2013a,b; Kool+2017

High resolution (AO) near-IR searches in LIRGs

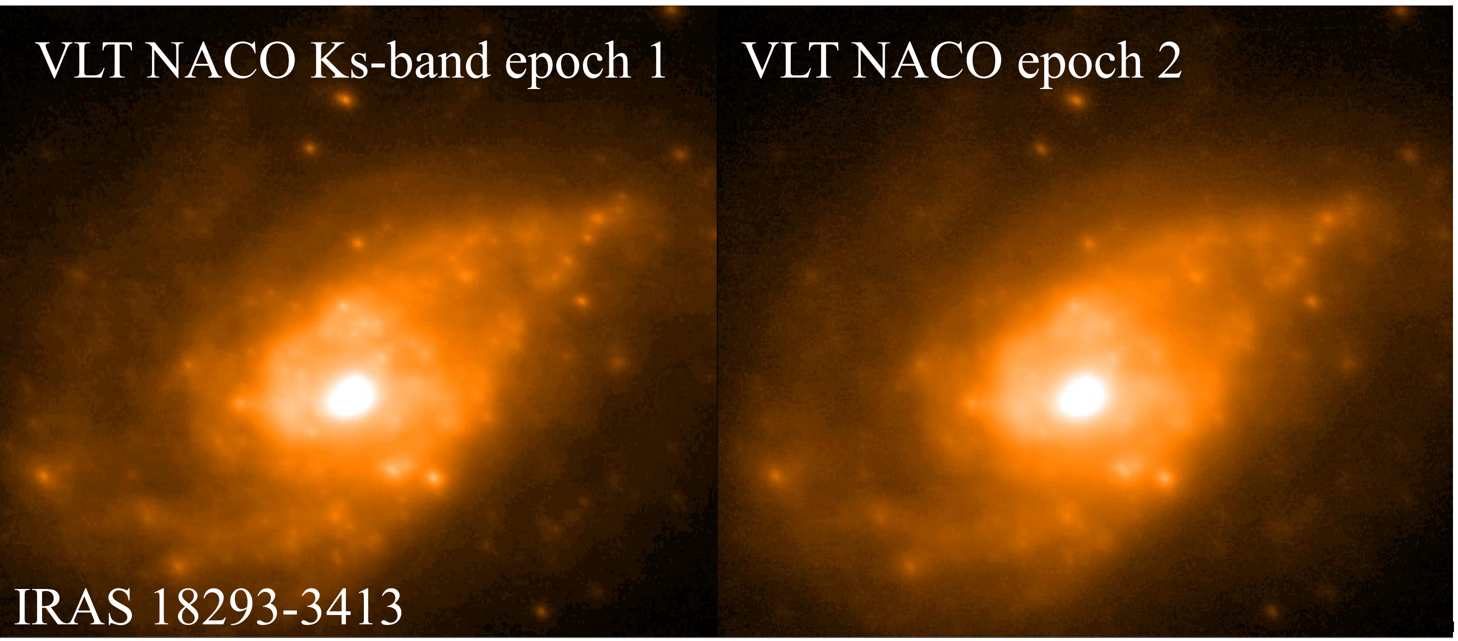
- Use AO to provide ~0.1” resolution in the near-IR *K*-band for the SN detection and study
- Observe the most promising LIRGs within ~120 Mpc (0.1” corresponds to <60pc)
    - ESO VLT + NACO (AO with NGS)
    - Gemini-N + ALTAIR/NIRI (AO with LGS)
    - Gemini-S + GeMS/GSAOI (MCAO with LGSs)
    - Keck II + NIRC2 (AO with LGSs)
- Follow-up in *JHK* (AO) photometry and radio (e.g. VLA) to confirm the SN nature and estimate extinctions from the near-IR colours

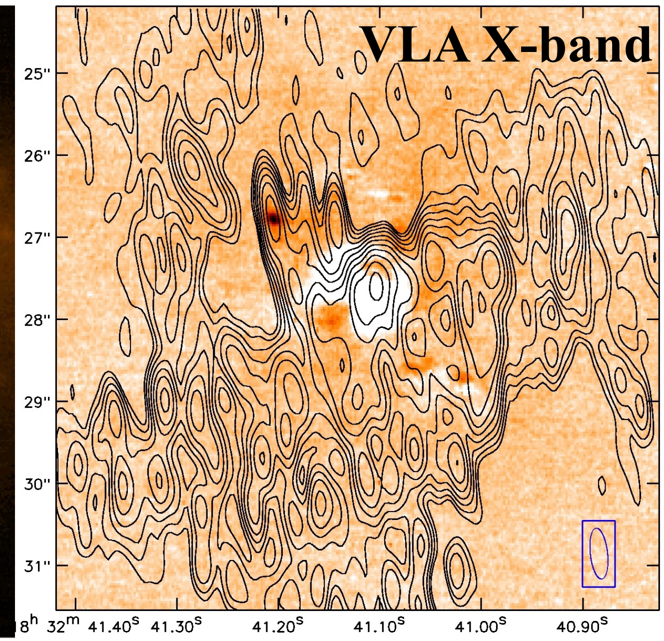


Mattila+2007; Perez-Torres+2007

High resolution (AO) near-IR searches in LIRGs

- Use AO to provide ~0.1” resolution in the near-IR *K*-band for the SN detection and study
- Observe the most promising LIRGs within ~120 Mpc (0.1” corresponds to <60pc)
    - ESO VLT + NACO (AO with NGS)
    - Gemini-N + ALTAIR/NIRI (AO with LGS)
    - Gemini-S + GeMS/GSAOI (MCAO with LGSs)
    - Keck II + NIRC2 (AO with LGSs)
- Follow-up in *JHK* (AO) photometry and radio (e.g. VLA) to confirm the SN nature and estimate extinctions from the near-IR colours

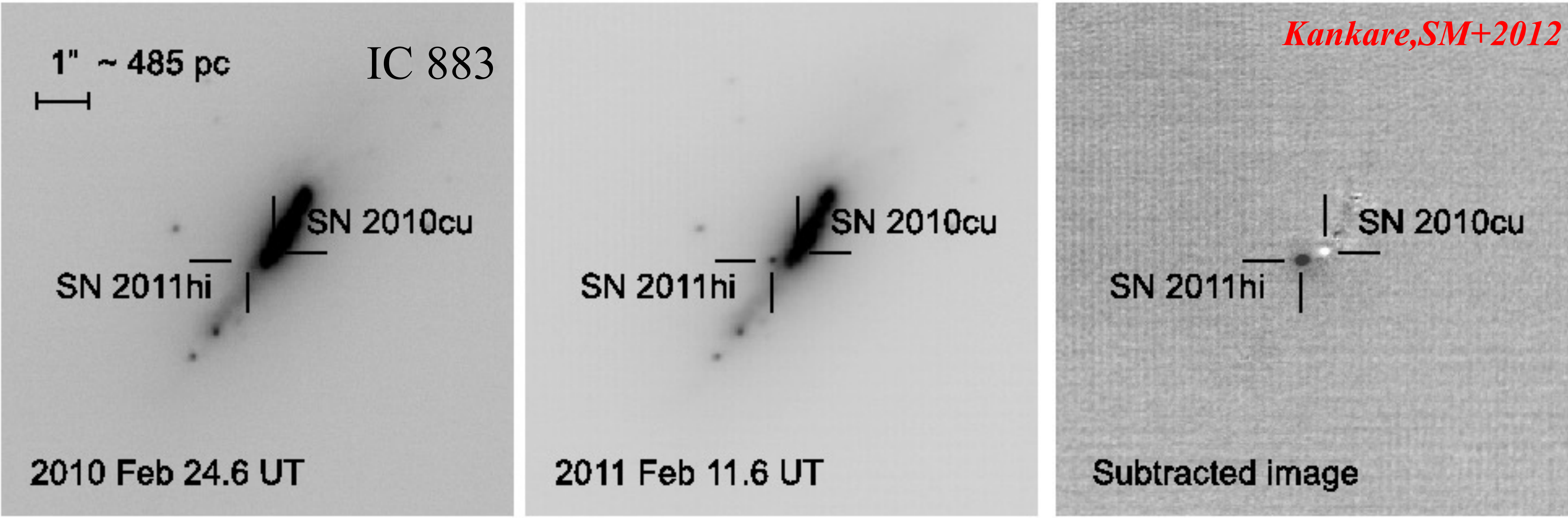




Mattila+2007; Perez-Torres+2007

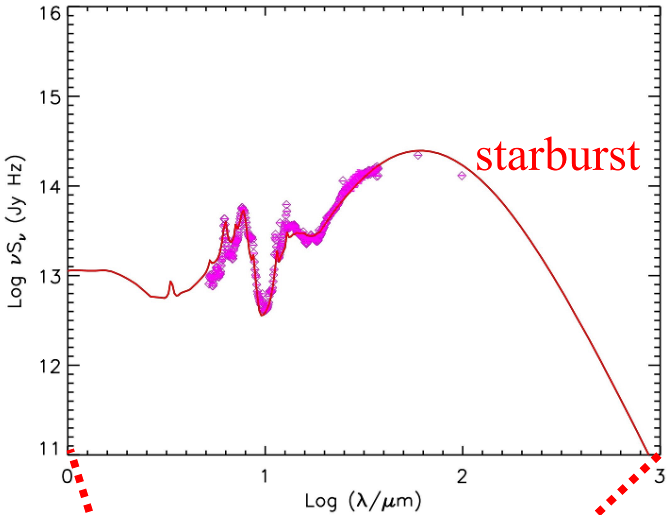
High resolution (AO) near-IR searches in LIRGs

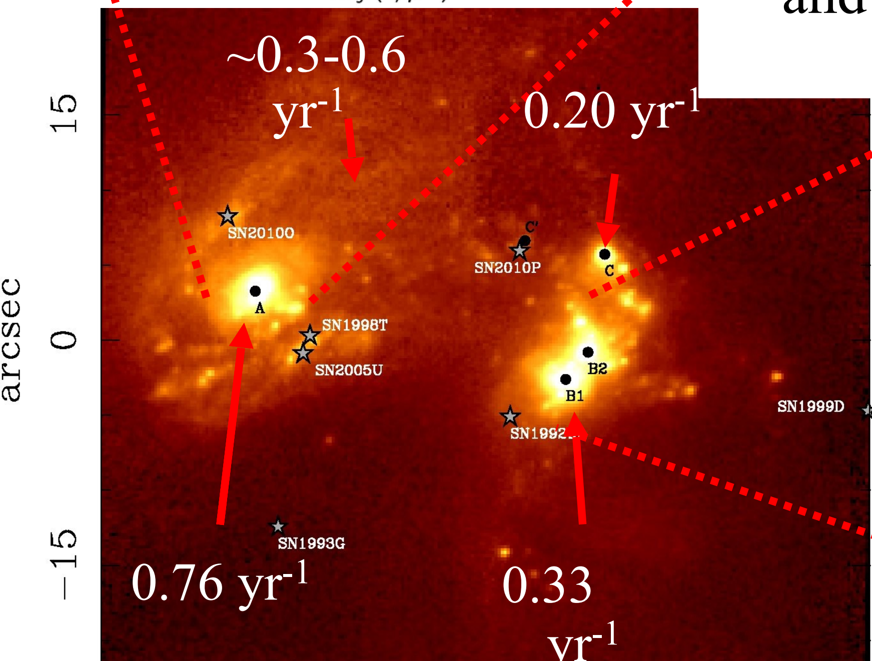
- Use AO to provide ~0.1" resolution in the near-IR *K*-band for the SN detection and study
- Observe the most promising LIRGs within ~120 Mpc (0.1" corresponds to <60pc)
  - ESO VLT + NACO (AO with NGS)
  - Gemini-N + ALTAIR/NIRI (AO with LGS)
  - Gemini-S + GeMS/GSAOI (MCAO with LGSs)
  - Keck II + NIRC2 (AO with LGSs)
- Follow-up in *JHK* (AO) photometry and radio (e.g. VLA) to confirm the SN nature and estimate extinctions from the near-IR colours

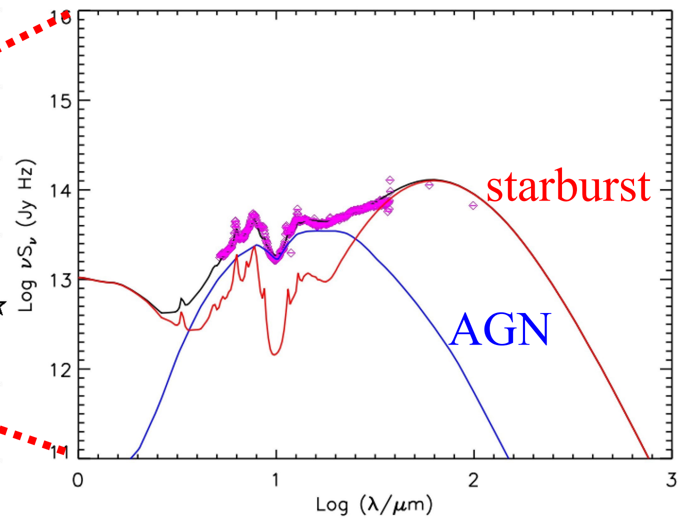


Estimate CCSN rates from the IR SEDs

- 5-38µm Spitzer spectra (Alonso-Herrero et al. 2009) 12, 25, 60 and 100µm IRAS photometry
- Fit the SEDs with AGN models of Efstathiou & Rowan-Robinson (1995) and starburst models of Efstathiou et al. (2000)
- Estimate the CCSN rate using the stellar population models of Bruzual & Charlot (2003), starburst age and SFR from the SED models



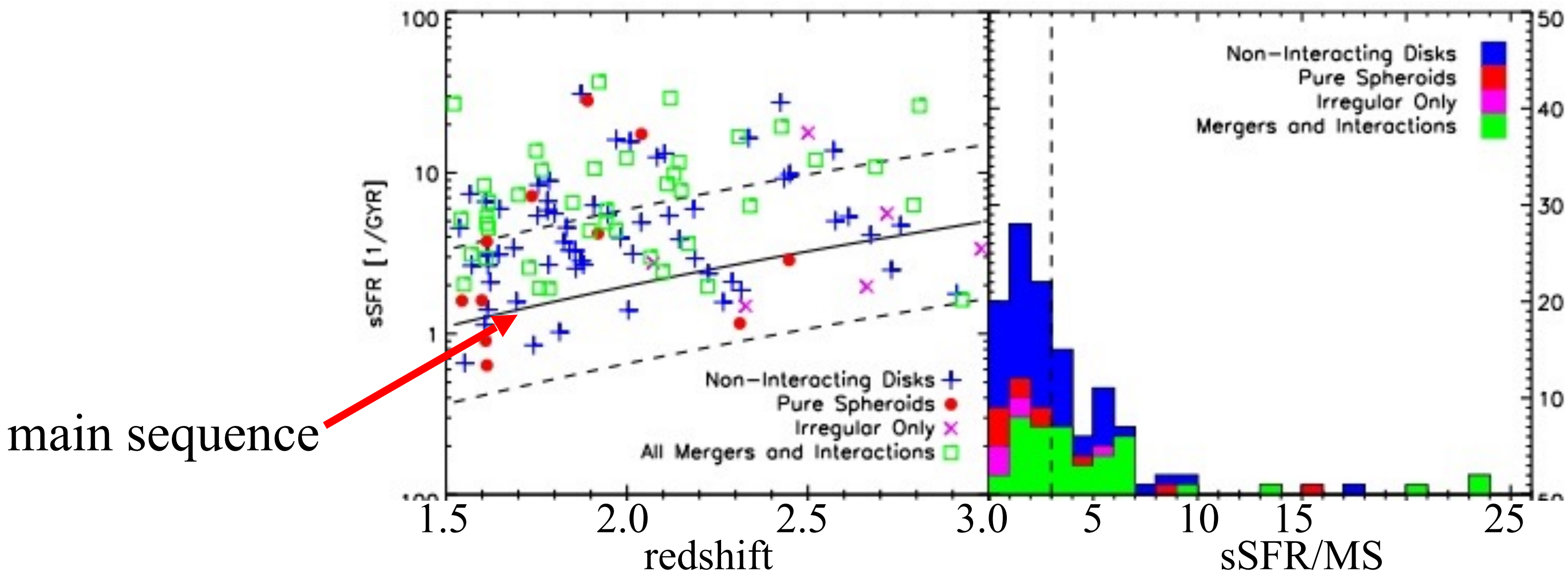




Mattila et al. (2012)

How many of the U/LIRGs at high-z are starbursting?

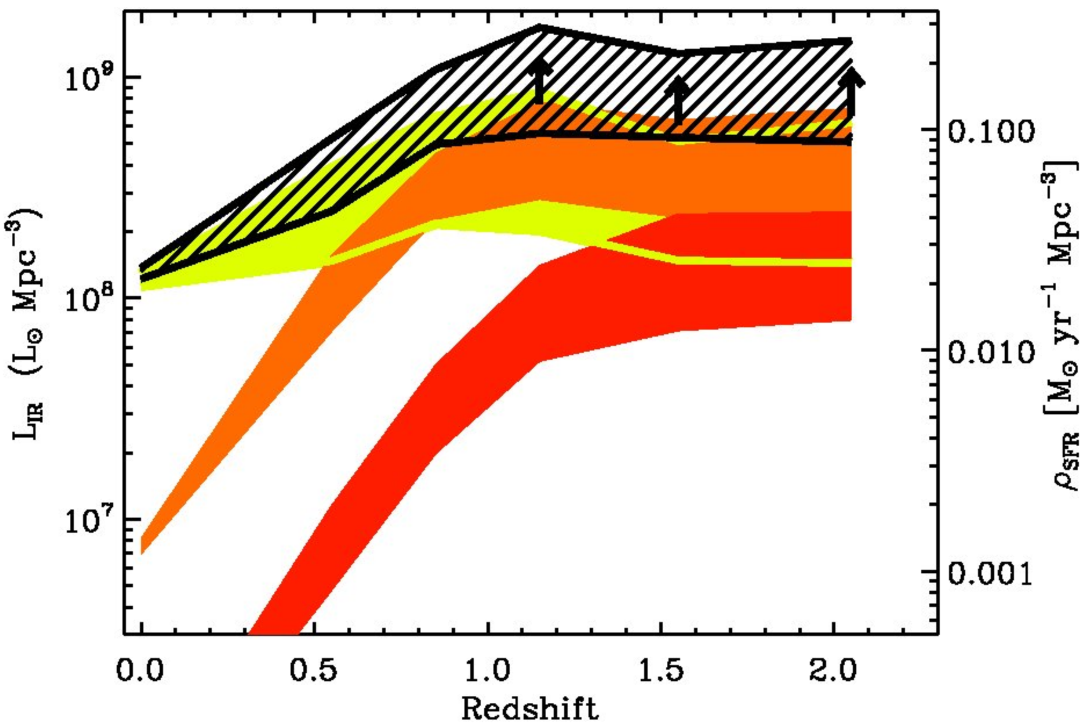
- U/LIRG population at high-z dominated by disk galaxies forming stars in 'normal' extended (main sequence) mode (Elbaz et al. 2011)
- Kartaltepe et al. (2011) combined deep Herschel and HST/WFPC3 near-IR imaging (CANDELS) of GOODS-S to study U/LIRGs at z ~ 1.5-3.0
  - **~42%** are starbursts with sSFR > 3 x sSFR(main sequence)
  - Assume similar missing SN fraction as observed for Arp 299

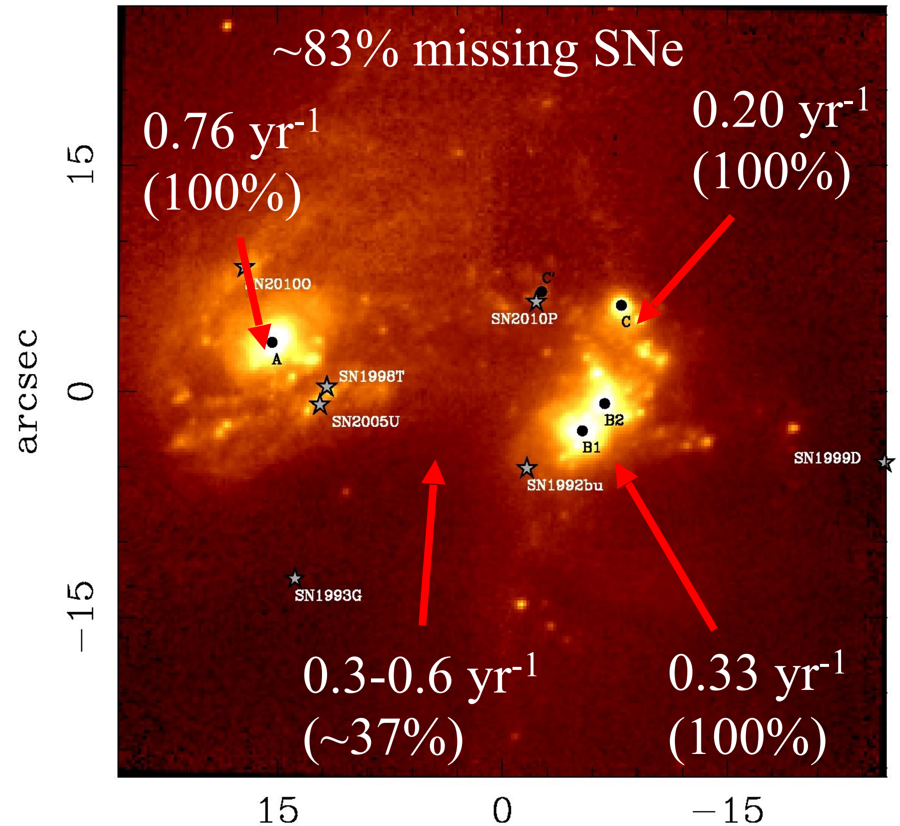


Kartaltepe et al. (2011)

SNe missed by rest-frame optical surveys

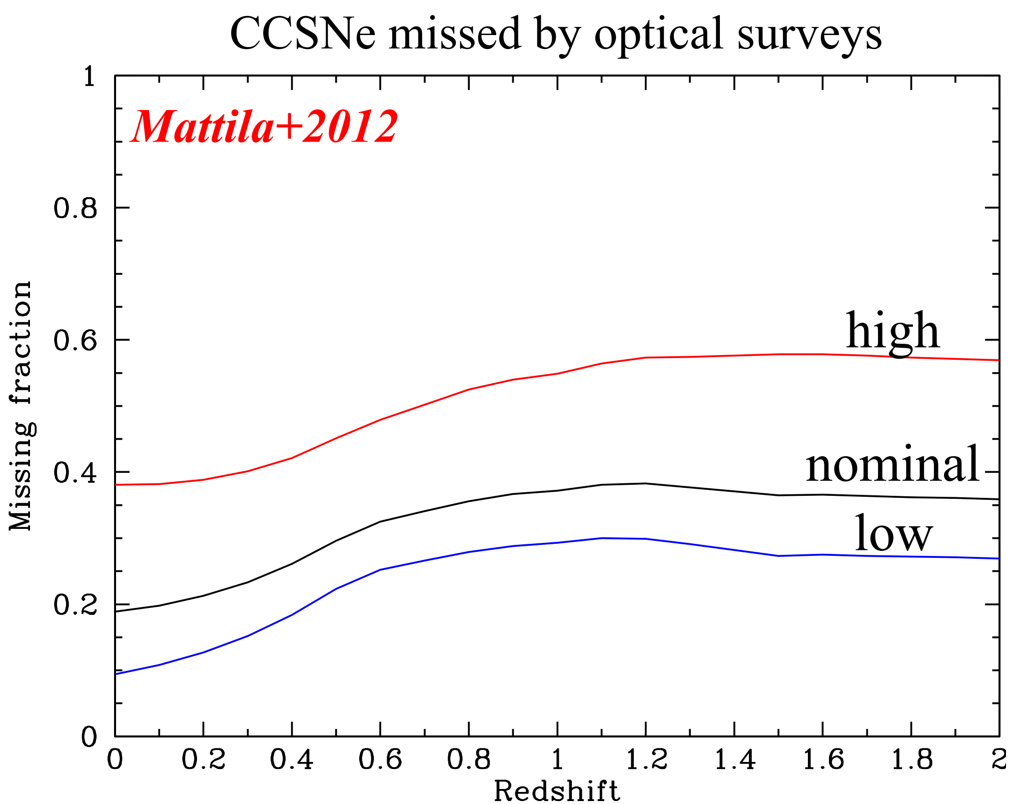
- Estimate the fraction of "missing" SNe in dusty galaxies as a function of redshift
  - **15%** missed in 'normal' galaxies, **83%** in local U/LIRGs (100% nuclear; 37% circumn.)
  - **83%** missed in starbursting and **37%** in non-starbursting high-z U/LIRGs

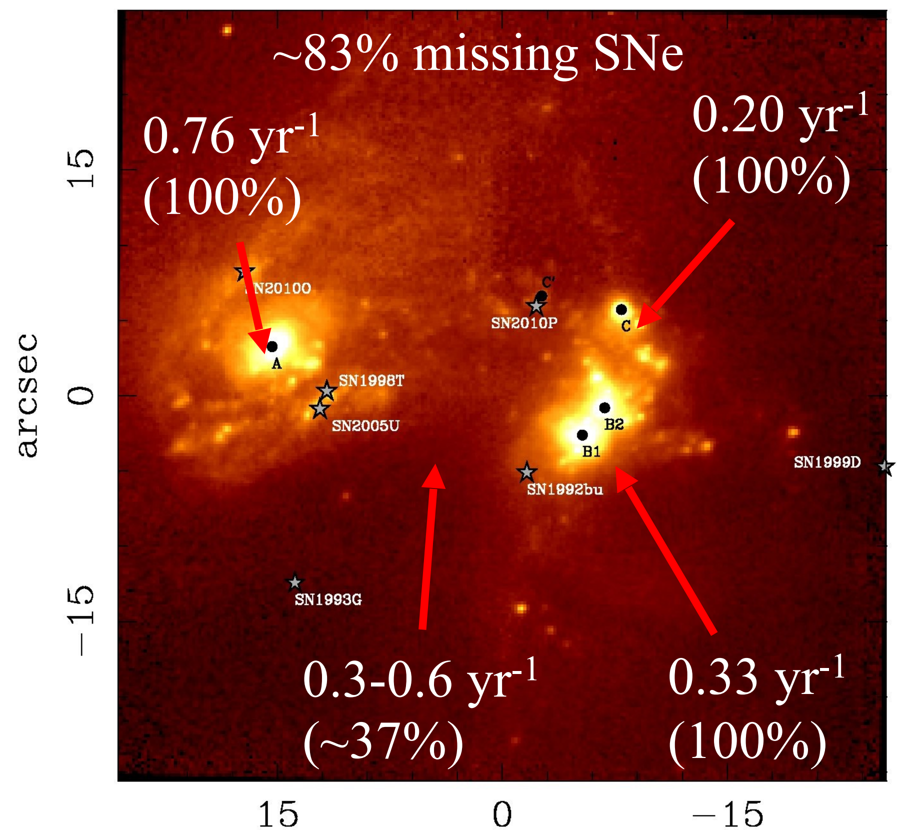




SNe missed by rest-frame optical surveys

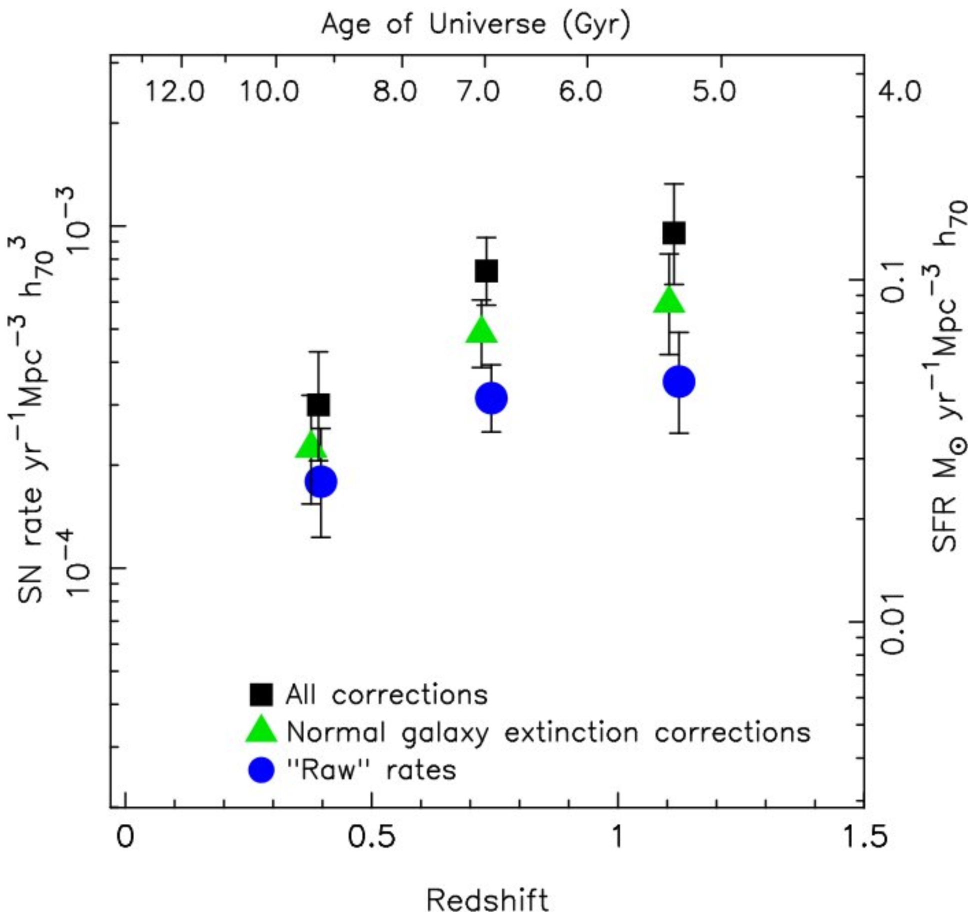
- Estimate the fraction of "missing" SNe in dusty galaxies as a function of redshift
  - **15%** missed in 'normal' galaxies, **83%** in local U/LIRGs (100% nuclear; 37% circumn.)
  - **83%** missed in starbursting and **37%** in non-starbursting high-z U/LIRGs





Effects of missing SNe on cosmic CCSN rates

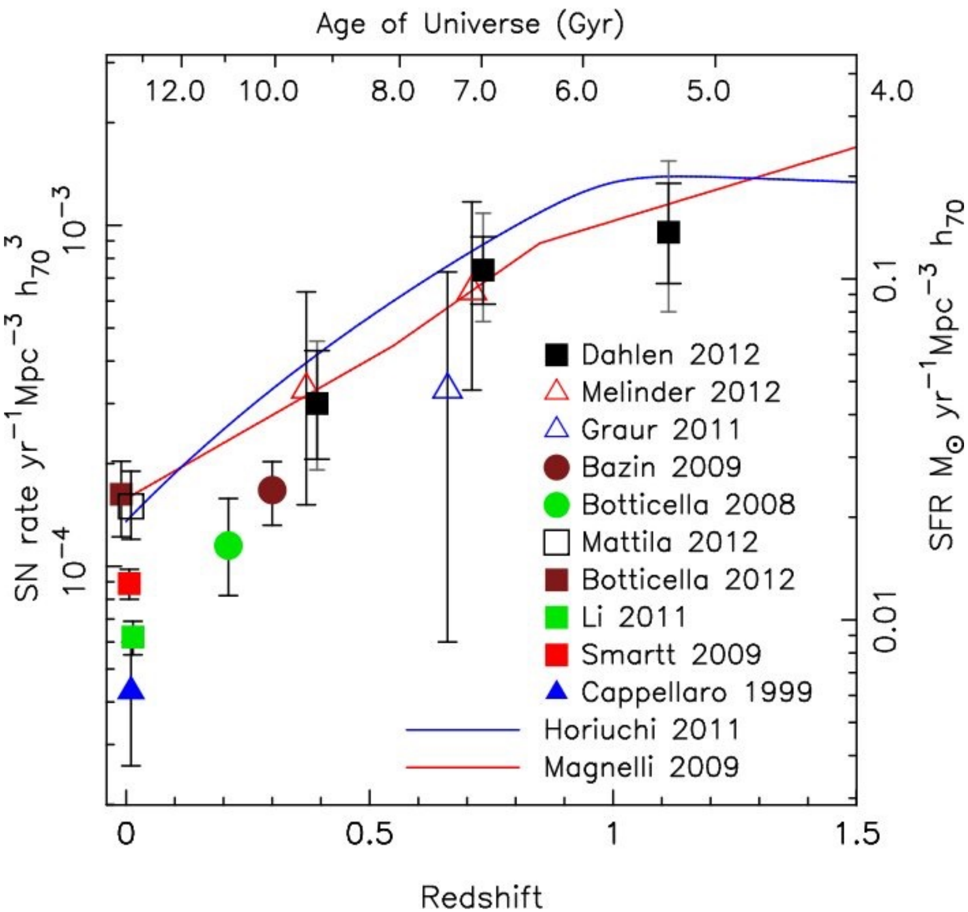
- Melinder 2012 and Dahlen 2012 core-collapse SN rates corrected for the “missing” SNe
- SN rates at z ~ 0.4-1.1 consistent with those expected from the cosmic SFR
- Systematic uncertainties in the CCSN rates significant at all redshifts



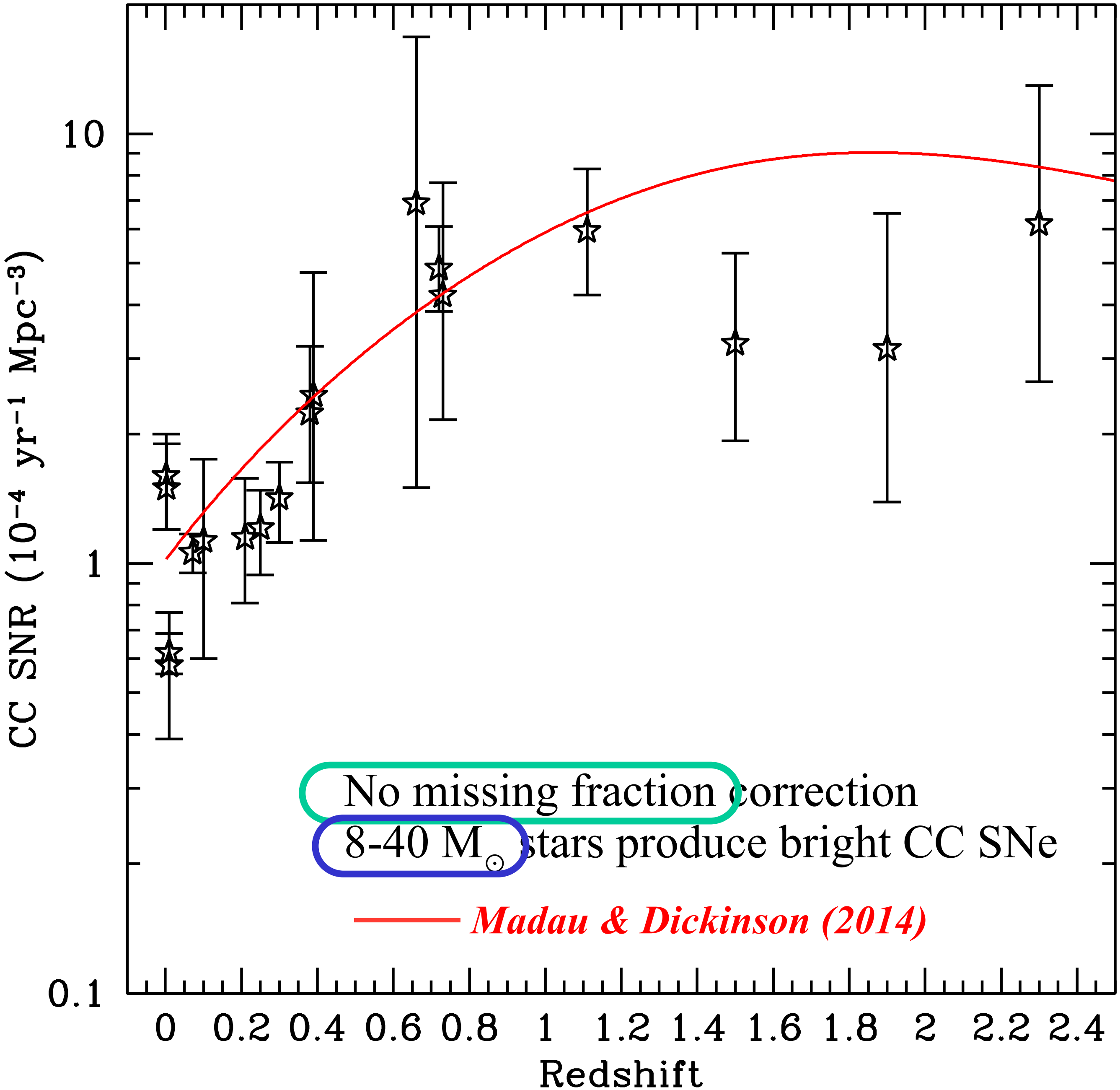
Melinder et al. (2012)
Dahlen et al. (2012)

Effects of missing SNe on cosmic CCSN rates

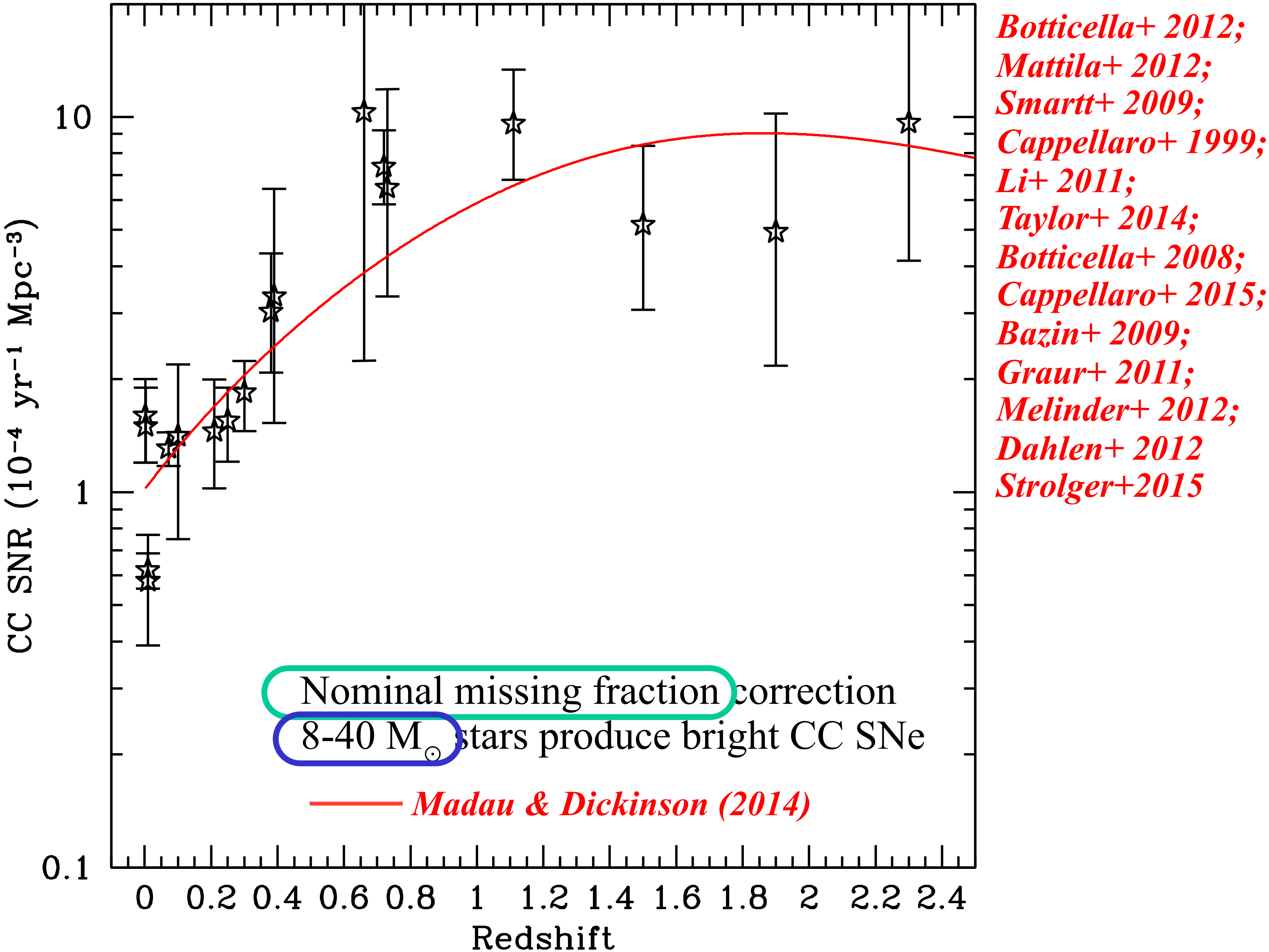
- Melinder 2012 and Dahlen 2012 core-collapse SN rates corrected for the “missing” SNe
- SN rates at z ~ 0.4-1.1 consistent with those expected from the cosmic SFR
- Systematic uncertainties in the CCSN rates significant at all redshifts



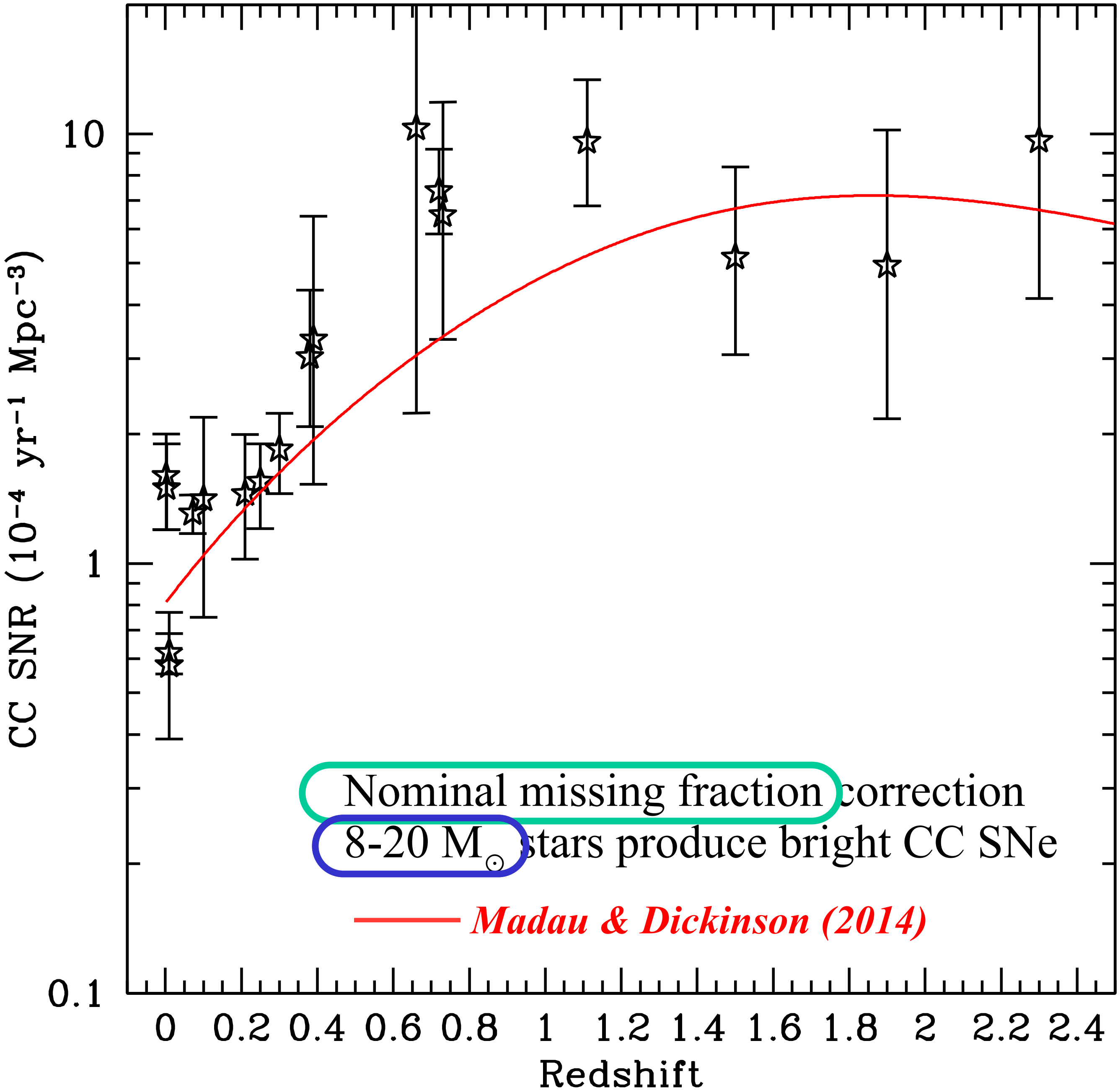
Melinder et al. (2012)
Dahlen et al. (2012)



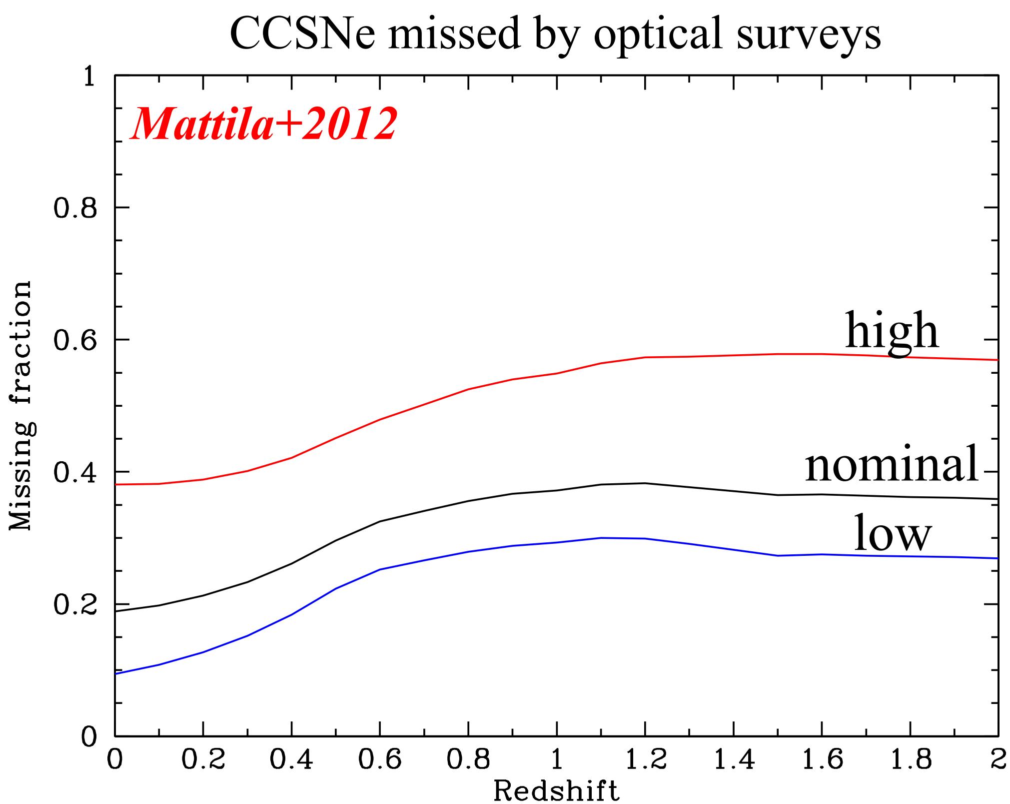
Botticella+ 2012; Mattila+ 2012; Smartt+ 2009; Cappellaro+ 1999; Li+ 2011; Taylor+ 2014; Botticella+ 2008; Cappellaro+ 2015; Bazin+ 2009; Graur+ 2011; Melinder+ 2012; Dahlen+ 2012 Strolger+2015

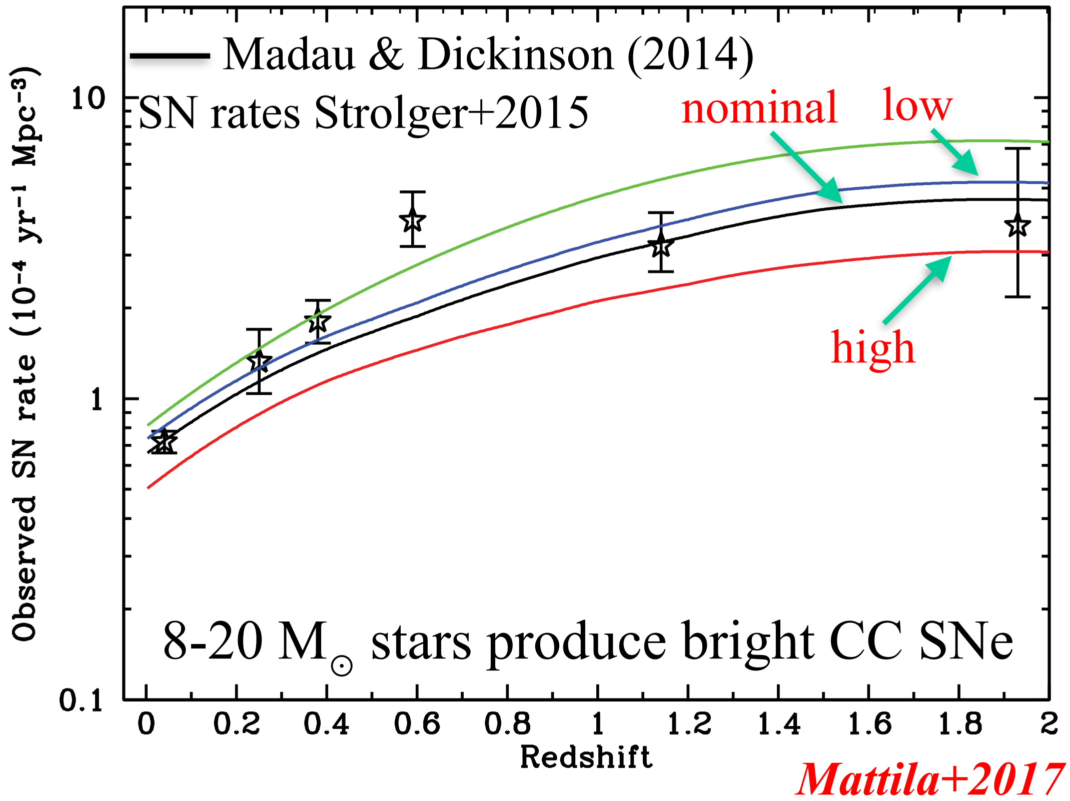


CC SNR (10^{-4} yr^{-1} Mpc^{-3})
10
1
0.1
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4
Redshift
Nominal missing fraction correction
8-40 $M_\odot$ stars produce bright CC SNe
Madau & Dickinson (2014)
Botticella+ 2012;
Mattila+ 2012;
Smartt+ 2009;
Cappellaro+ 1999;
Li+ 2011;
Taylor+ 2014;
Botticella+ 2008;
Cappellaro+ 2015;
Bazin+ 2009;
Graur+ 2011;
Melinder+ 2012;
Dahlen+ 2012
Strolger+2015

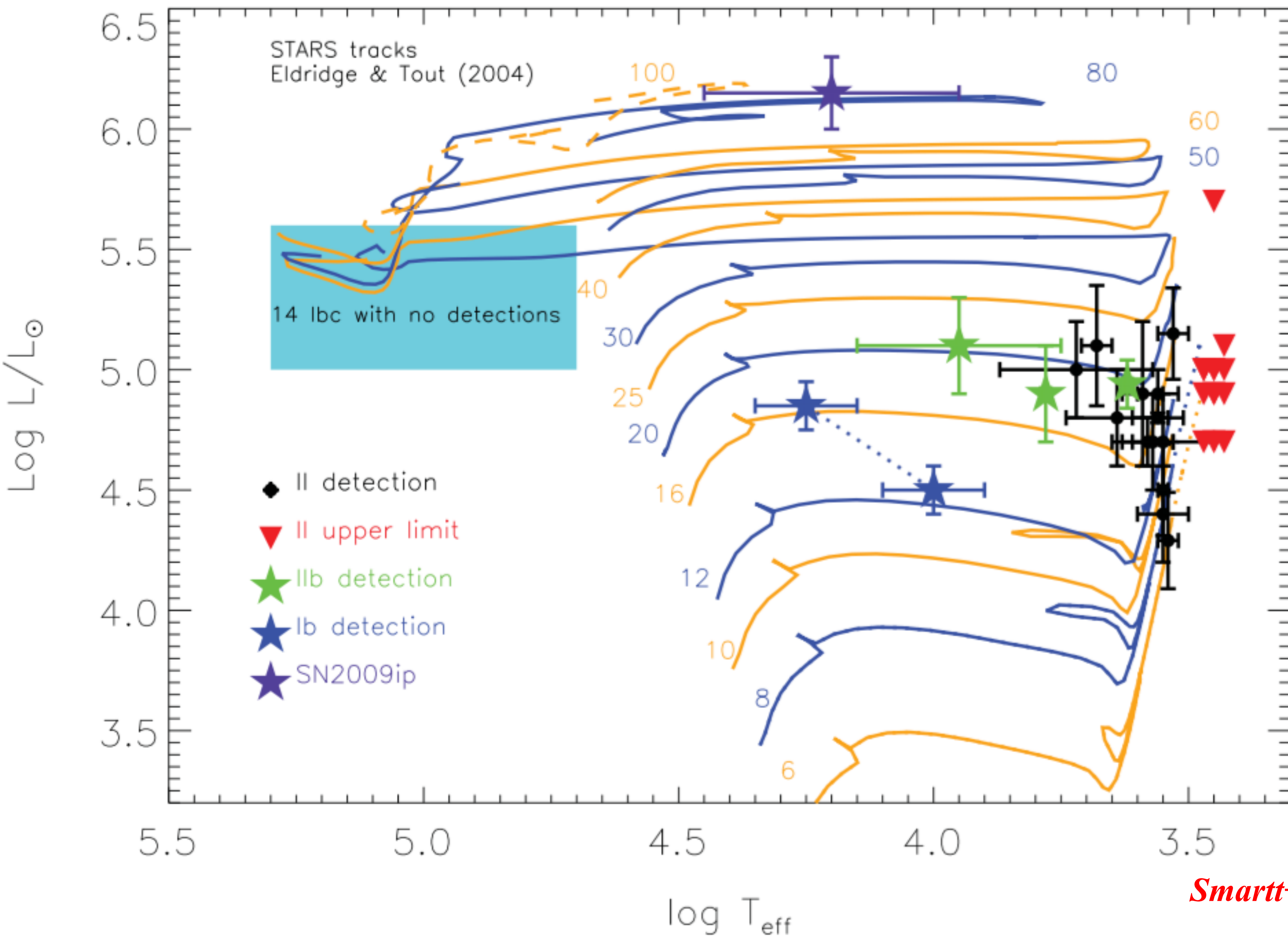


Botticella+ 2012; Mattila+ 2012; Smartt+ 2009; Cappellaro+ 1999; Li+ 2011; Taylor+ 2014; Botticella+ 2008; Cappellaro+ 2015; Bazin+ 2009; Graur+ 2011; Melinder+ 2012; Dahlen+ 2012 Strolger+2015





Core-collapse SN rates are consistent with those expected from the cosmic SFR
Systematic uncertainties in the SN rates significant at all redshifts


STARS tracks
Eldridge & Tout (2004)
100
80
60
50
40
30
25
20
16
12
10
8
6
14 Ibc with no detections
II detection
II upper limit
IIb detection
Ib detection
SN2009ip
Log L/L⊙
log T eff
6.5
6.0
5.5
5.0
4.5
4.0
3.5
5.5
5.0
4.5
4.0
3.5

Smartt+2015

Summary

- Supernovae in the (circum)nuclear regions of galaxies missed due to extinction, searches lacking a sufficient spatial resolution and/or due to 'observer bias'
- High spatial resolution near-IR and radio observations provide a powerful combination for the detection and detailed study of *heavily obscured* nuclear SNe in U/LIRGs
- Detailed comparison between SN rates and cosmic SF history can provide a useful consistency check and information on the mass range for core-collapse SN progenitors
- JWST and ELT can extend these studies well beyond the peak of the cosmic SFR