SN rates from **SUDARE** survey
SUpernova **D**iversity **A**nd **R**ate **E**volution with **VST** telescope

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Supernove, Hypernove and Binary Driven Hypernove,
Pescara - June 20-30, 2016

Overview & Aims

- *SNe as endpoints of stellar evolution*
- *SN classes and main issues*
- *SN rates*

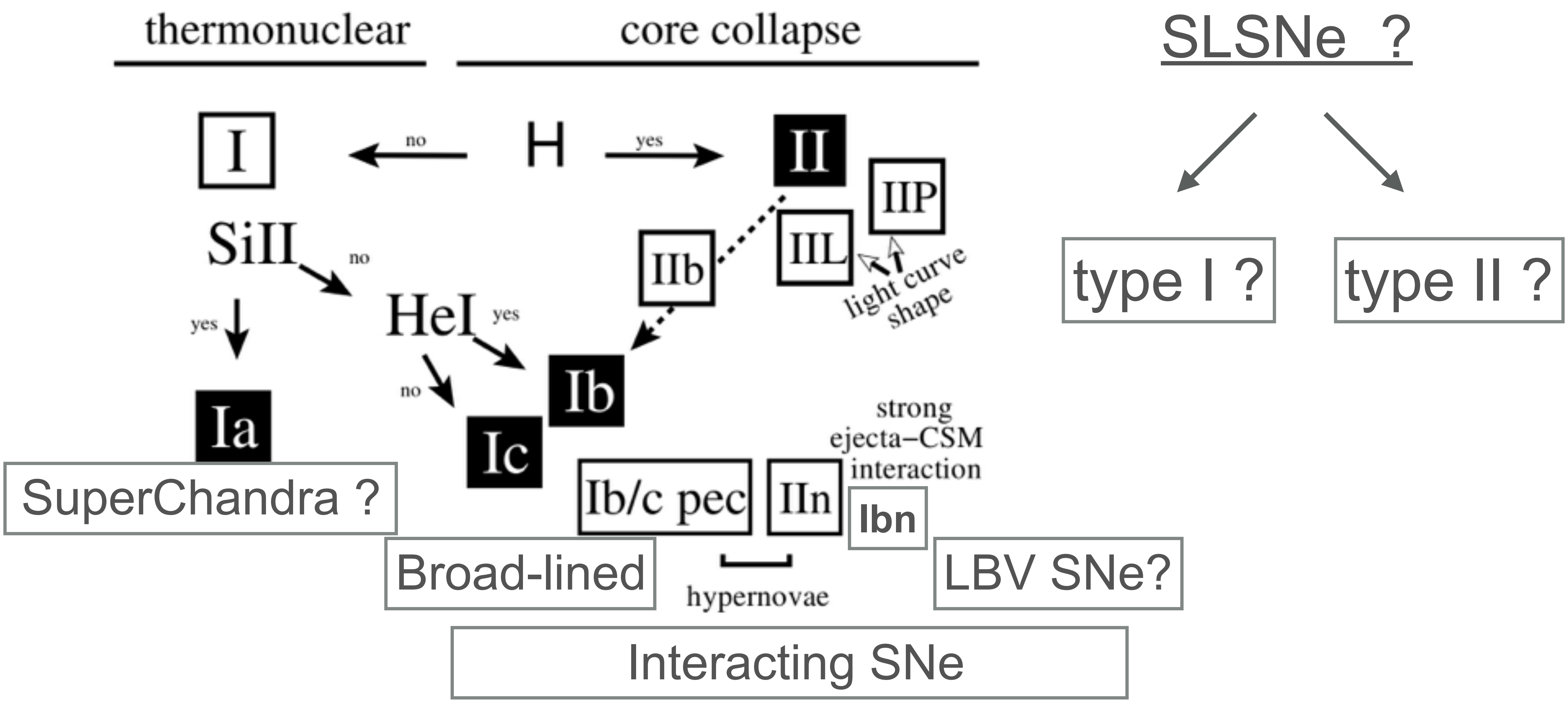
SUDARE

- *survey strategy and pipeline*
- *SN sample*
- *galaxy sample*

Results

- *SN rates per volume and stellar mass units*
- *SN rates as a function of cosmic time*
- *SN rates as a function of galaxy colour, mass, SFR & sSFR*

SN classes



Turatto 2003

SNe Core Collapse
(Type II, Ib/c, GRB-SNe)

$M > 8 \pm 1 M_\odot$

lack of progenitors above $\sim 20 M_\odot$*?*

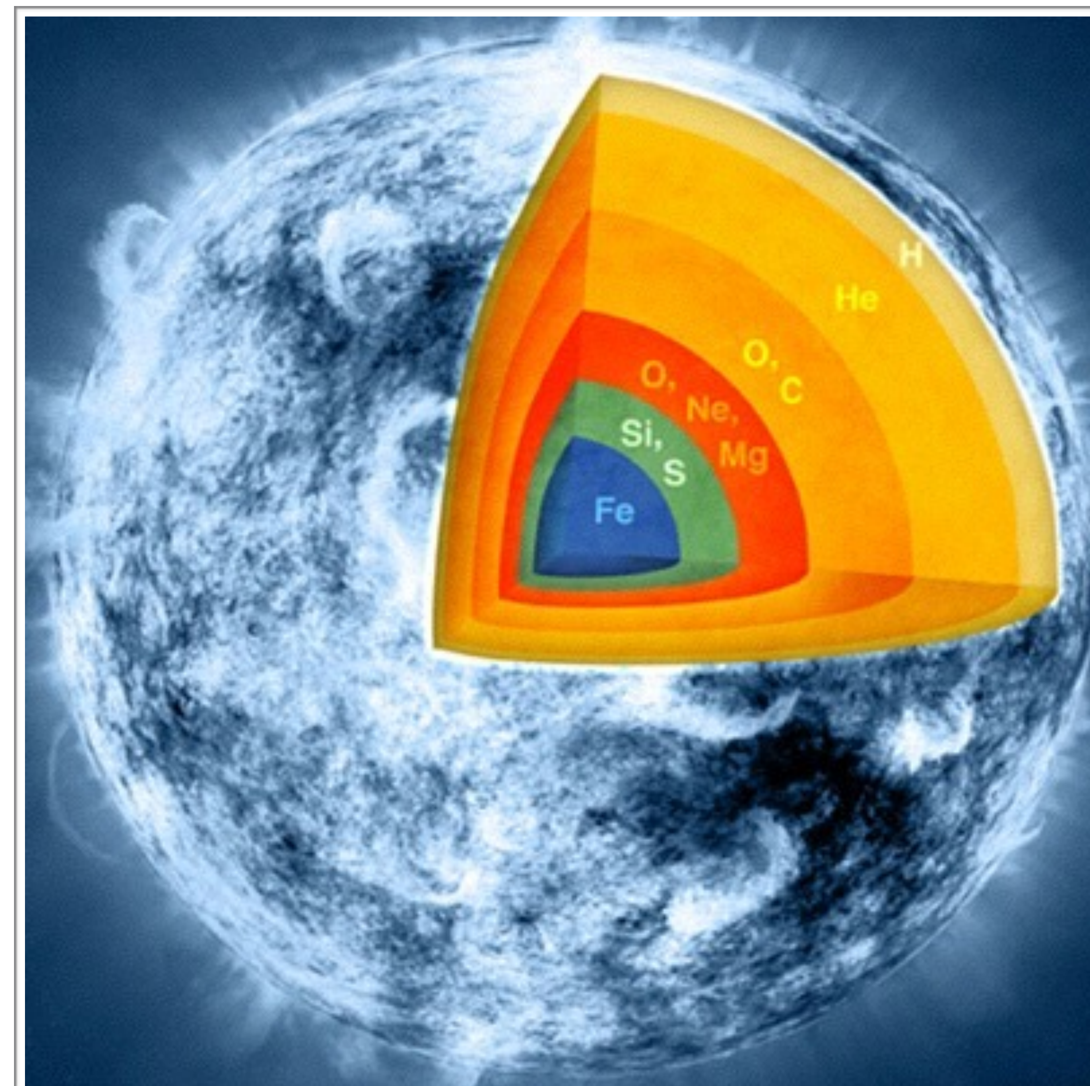
LBV luminous explosion, new mechanism?

SLSNe new types ?

IIP and few Ib/c
progenitors have been detected
in HST pre-explosion images
within 30 Mpc

occur in late type galaxies
trace the SFR

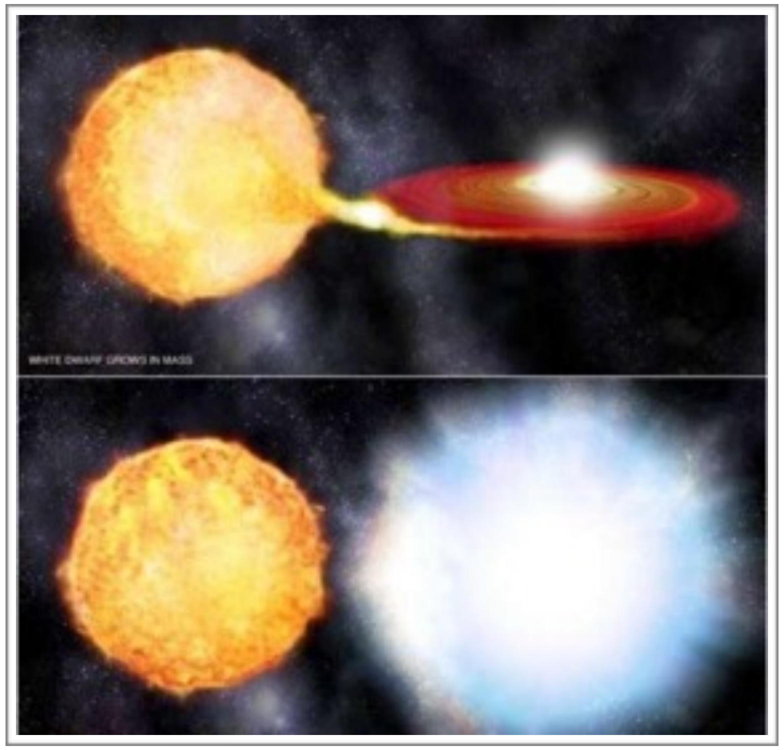
Smartt 2009
Eldridge+2013



Credit: NASA

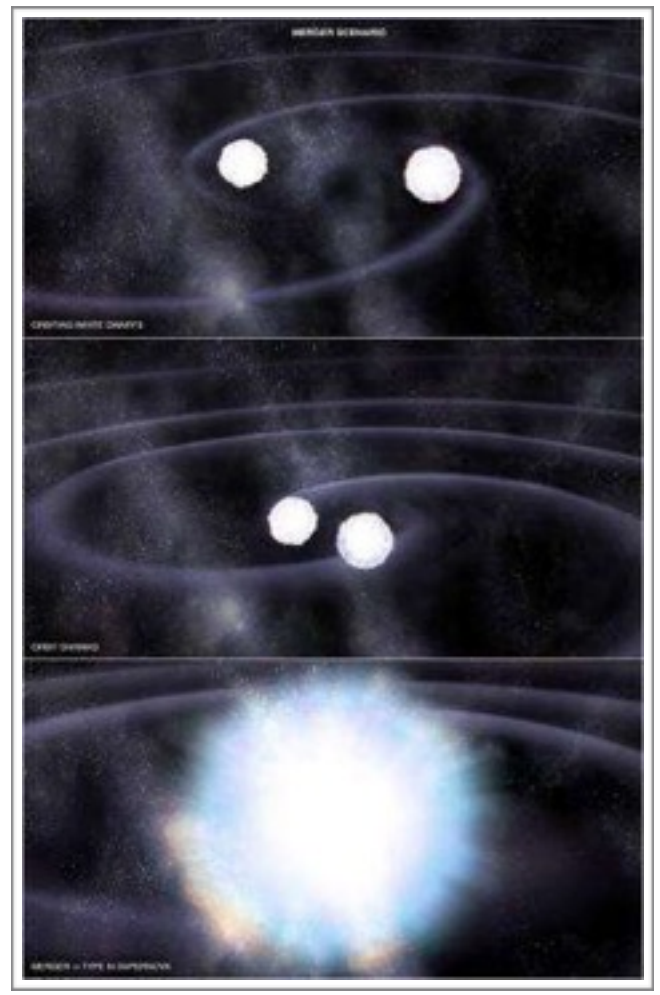
Thermonuclear SNe (Ia)

SD



Credit: NASA/CXC/M Weiss

DD



?

CD
DDet
WD-WD collision
...

Whelan & Iben 1973
Tutukov & Yungelson 1981

CO WD

$$M_{Ch} \approx 1.44 M_{\odot}$$

$$nonrotating \;\; \sim 1.38 M_{\odot}$$

Arnett 1969, Nomoto 1982

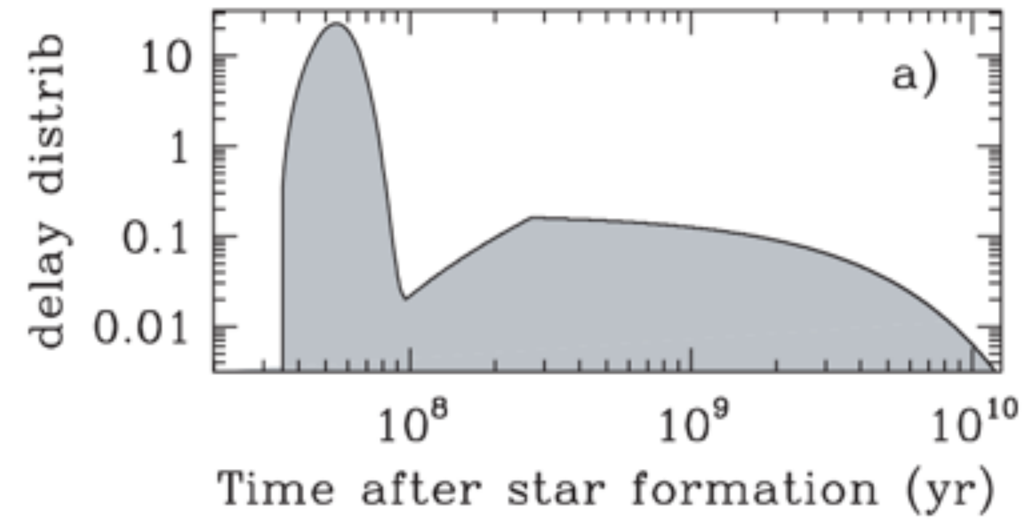
details of binary evolution, identity of progenitor systems
explosion mechanisms?

Delay Time Distribution

two distinct populations of progenitors

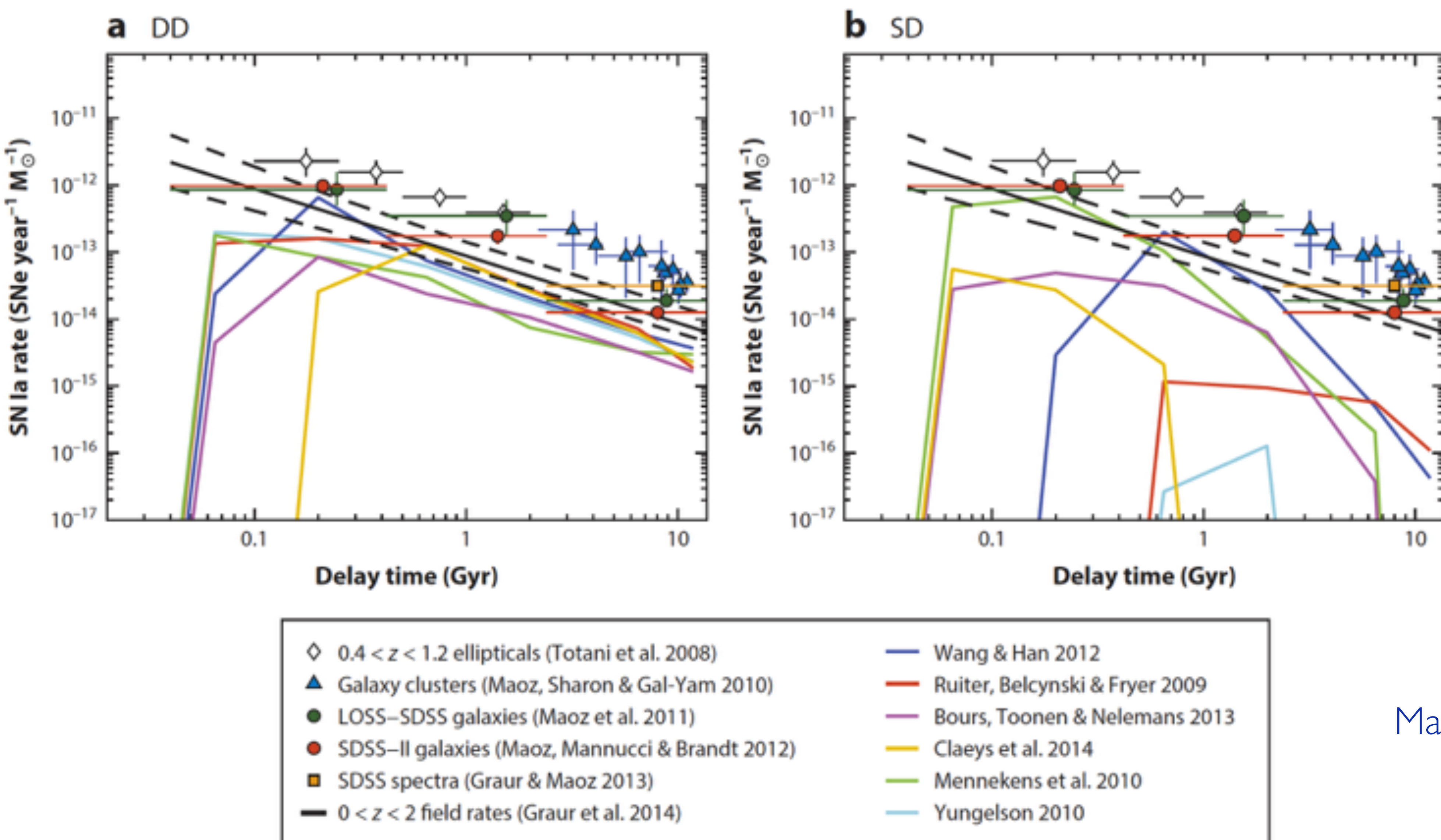
Mannucci, Della Valle & Panagia 2006

“prompt” ~ 10^8
“tardy” > 10^9



$$\Psi(t) \propto t^{-s}$$

DTD is power law

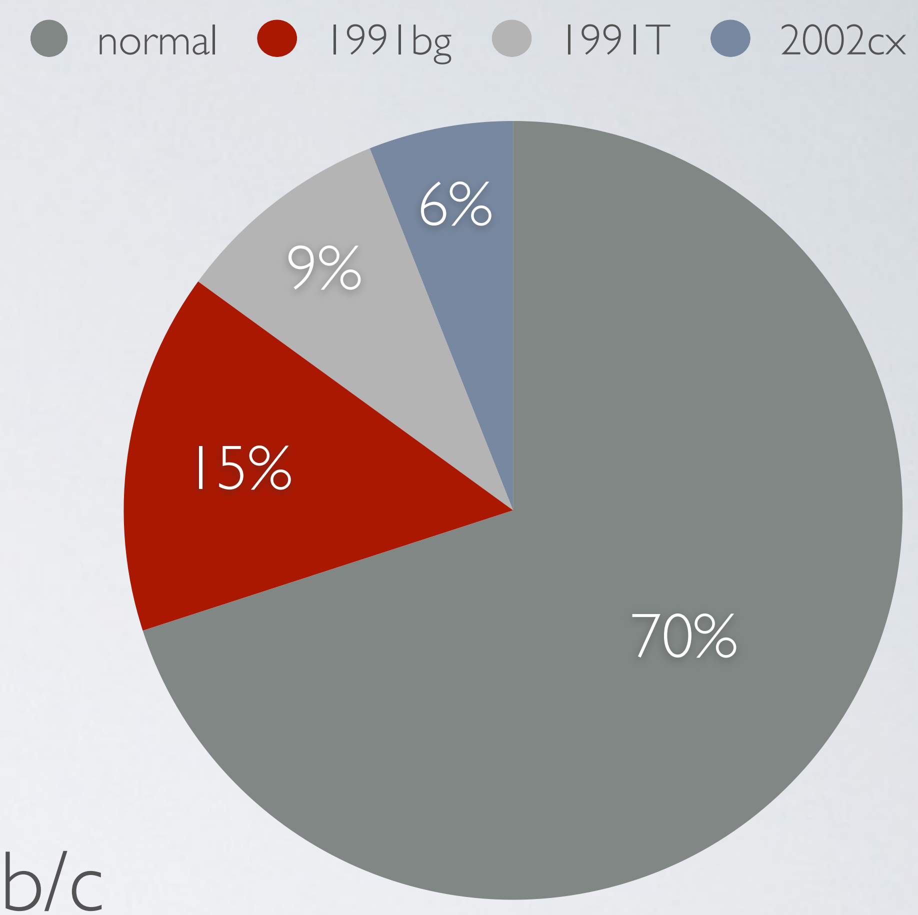


s~1 best-fit model

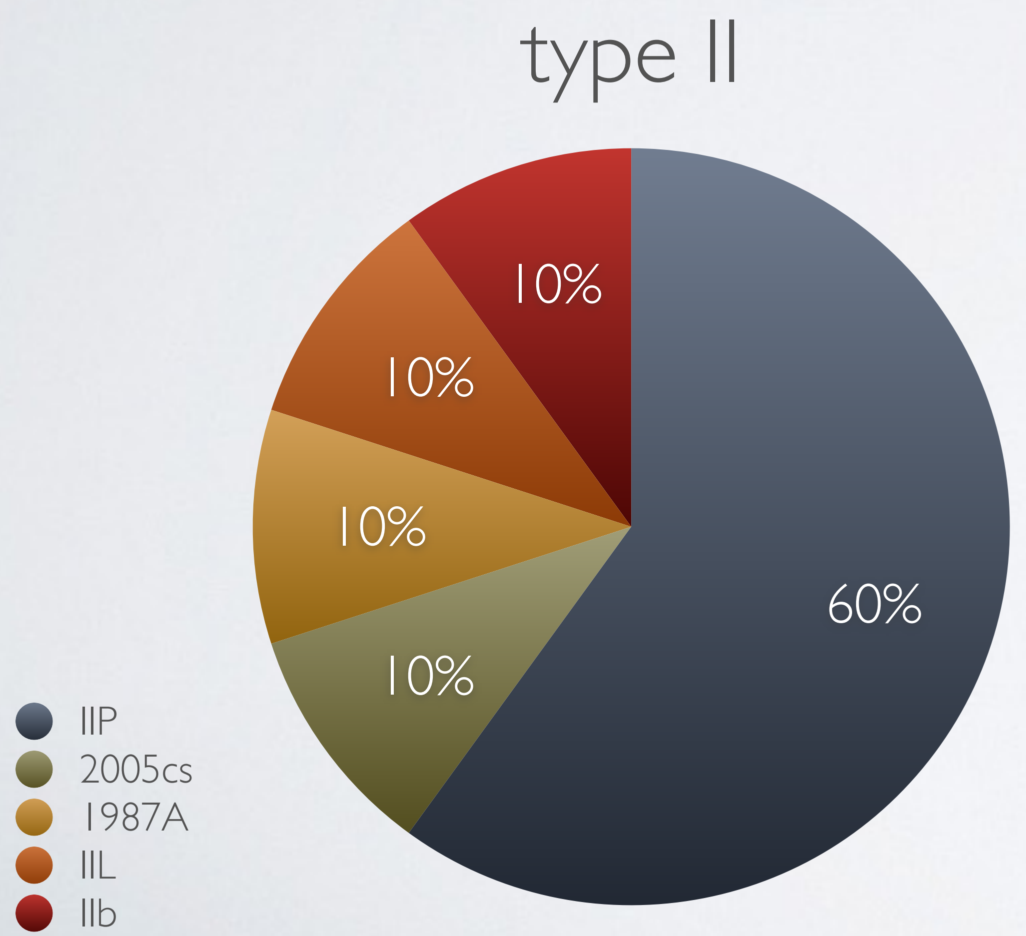
Maoz, Mannucci & Nelemans 2014

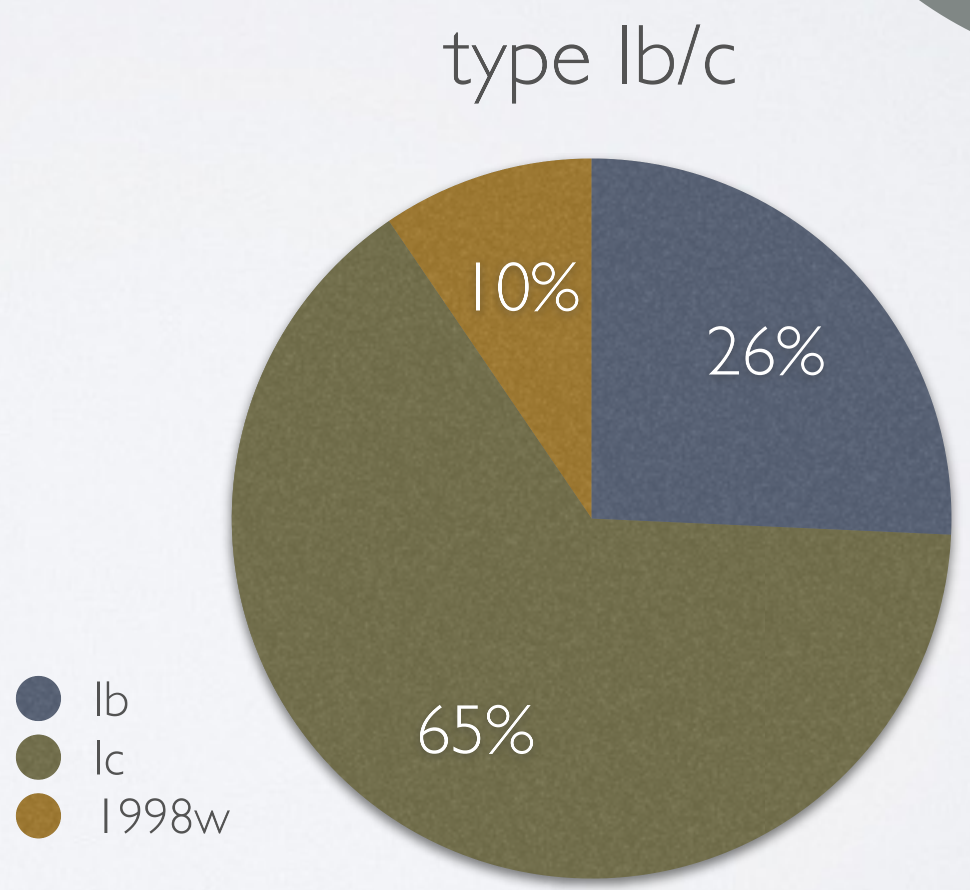
Fraction of Ia & II SNe per subtypes

over-luminous SN 1991T
under-luminous SN 1991bg
peculiar 2002cx



Li+2011a





Pastorello+2004
Podsiadlowsky+2004

SUDARE

SUpernova **D**iversity **A**nd **R**ate **E**volution

conducted on VST (VLT Survey Telescope) telescope at ESO

monitoring two of the best studied extragalactic fields: CDFS & COSMOS

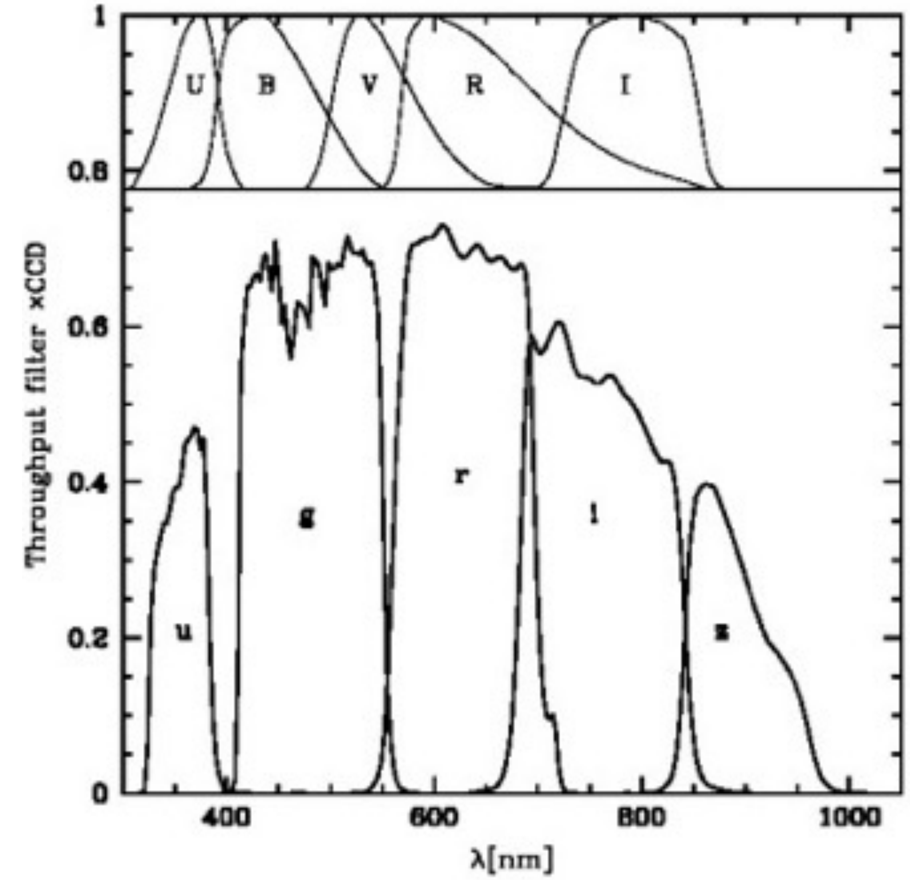
to measure rates of different SNe in the redshift range 0.1 < z < 0.8

117 SNe & ~130000 galaxies in CDFS1, CDFS2 and COSMOS pointings up to z < 1

VST - VLT Survey Telescope

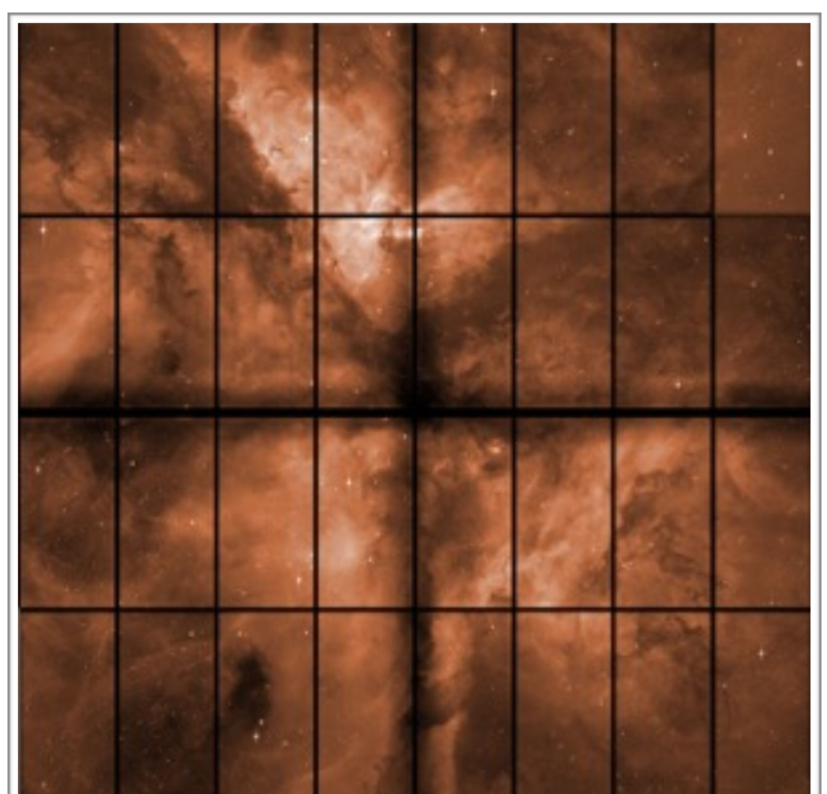
Capaccioli & Schipani 2011

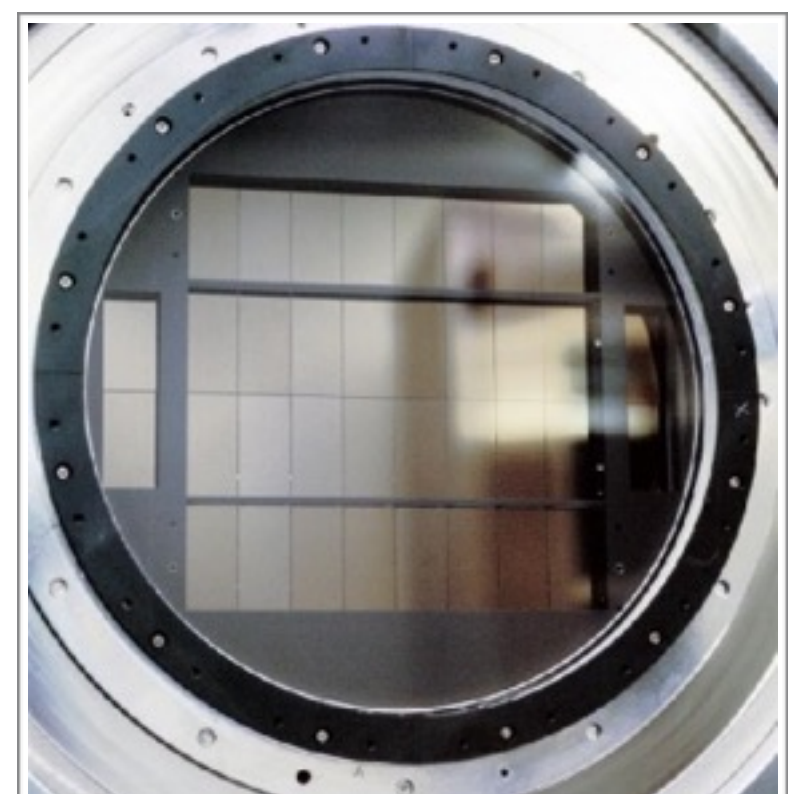
OmegaCAM camera
2.6m primariy morror
u–z (0.3–1 μ)
8 × *4* CCDs *4k* × *2k* pixels
1deg^2 with *0.214"pix*$^{-1}$



OmegaCAM

Kuijken 2011

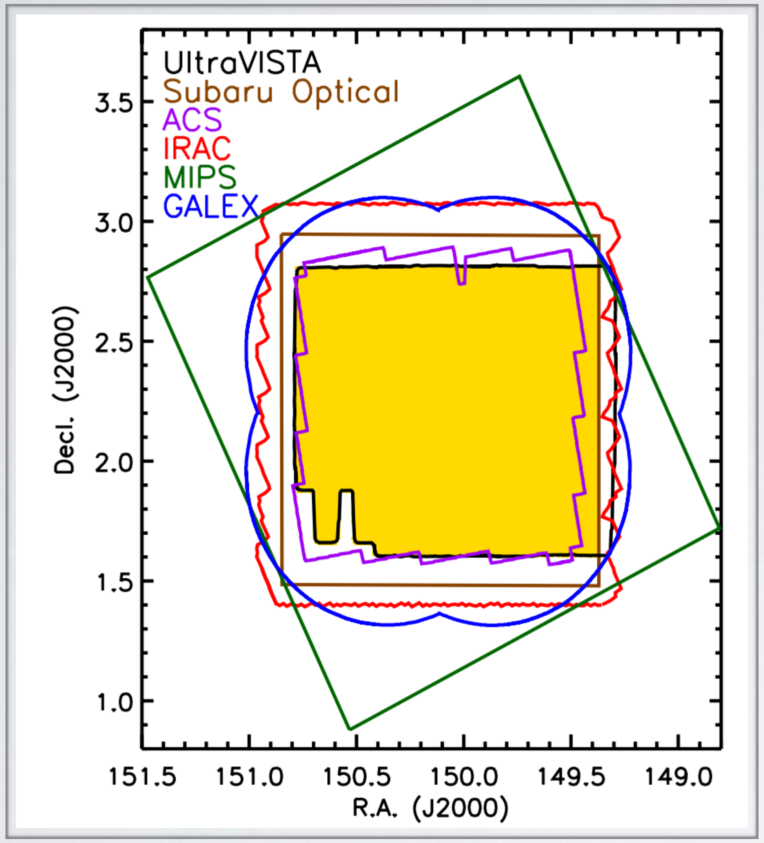




Credit: ESO

SUDARE on CDFS & COSMOS fields

Cosmic Evolutionary Survey



1 deg^2

g, r, i - SUDARE, P.I. Cappellaro - INAF GTO

SN search

0 < z < 1

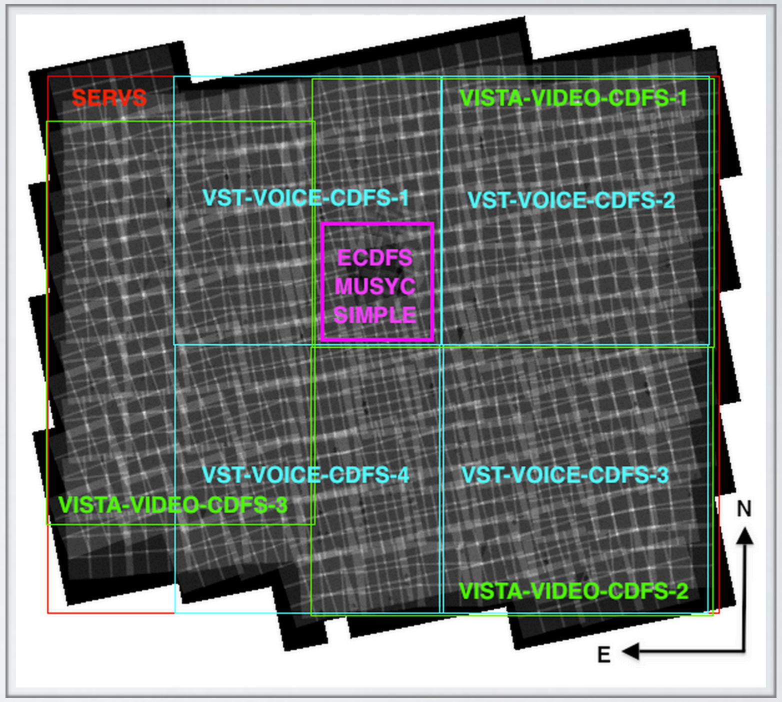
4 year rolling search

cadence:

r-band every 3d 30min

g,i-bands every 10d

Chandra Deep Field South



4 deg^2

g, r, i - SUDARE

P.I. Pignata - Chilean Time

VST-Tube & SUDARE pipelines

VSTTube pipeline

raw images

flat fielding

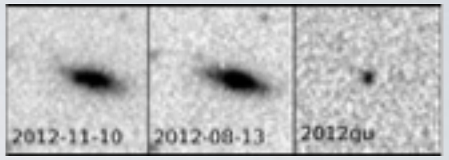
illumination correction

dithered images → stacked image

Grado+2012, De Cicco+2015

SUDARE pipeline

difference image



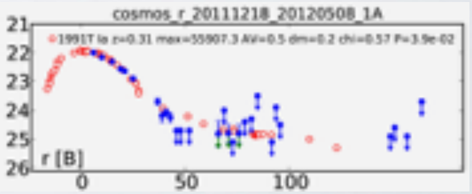
transient detection

candidates ranking,
visual confirmation

association with host galaxies

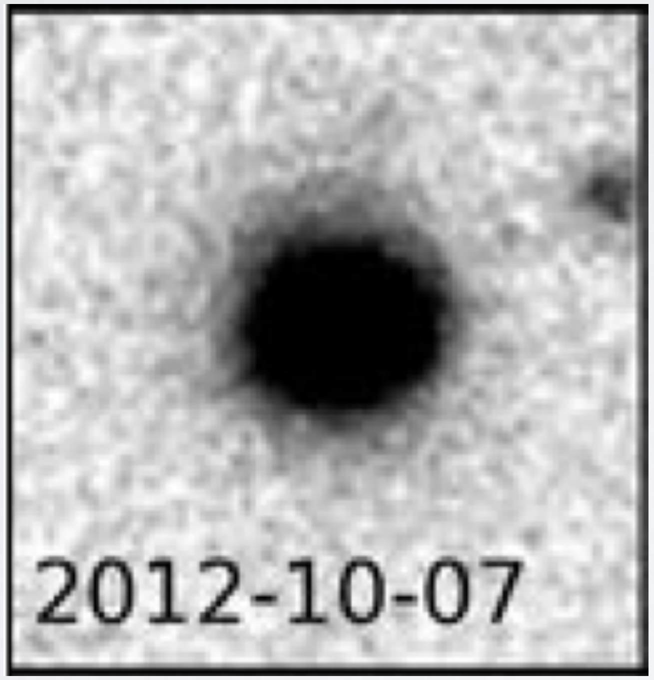
PSF & aperture photometry

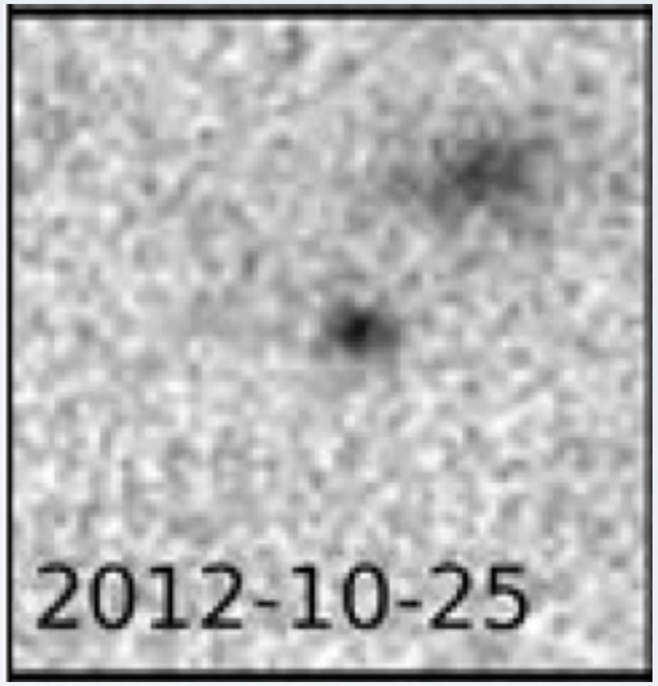
photometric typing



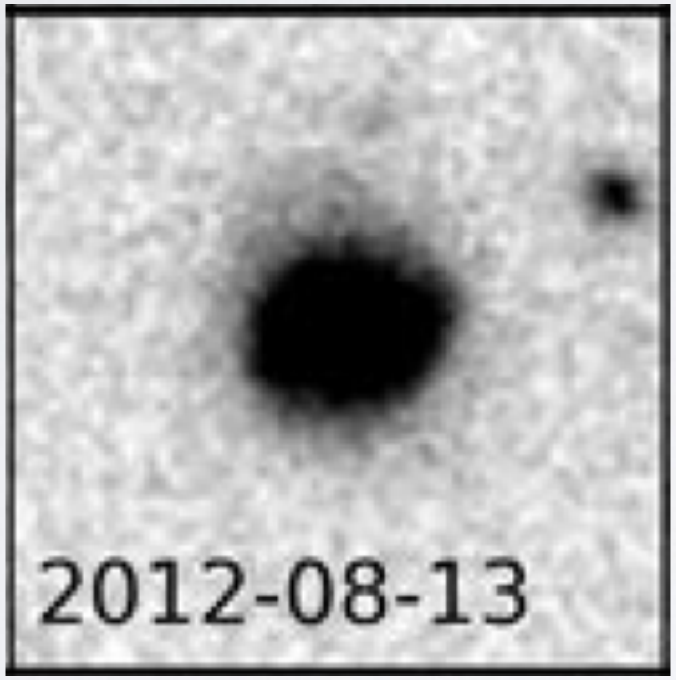
Cappellaro+2015

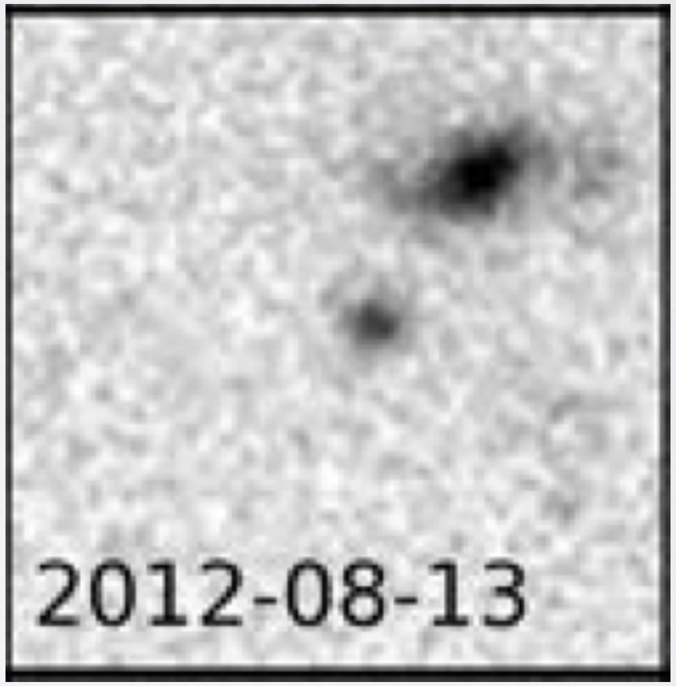
search image



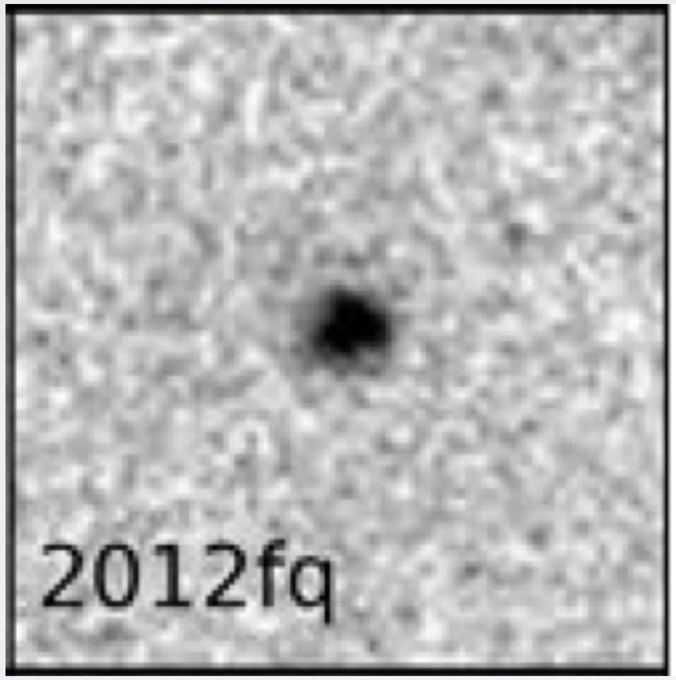


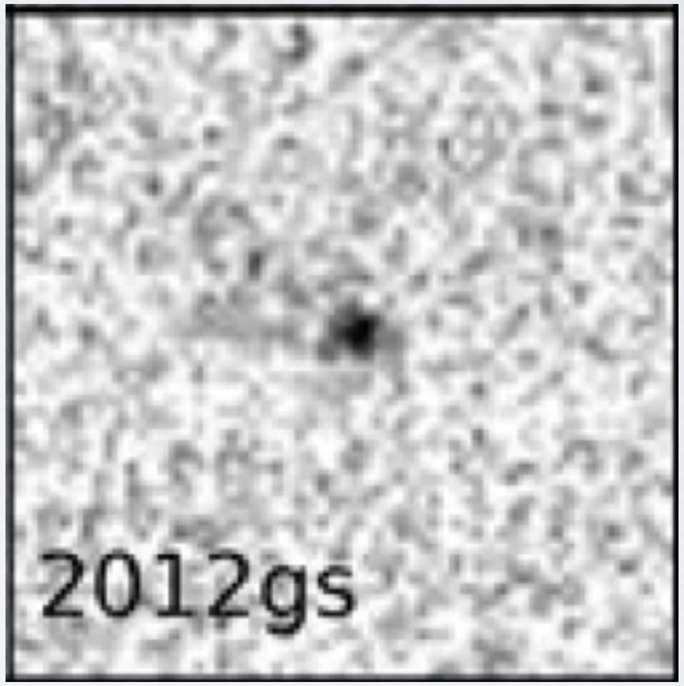
template image





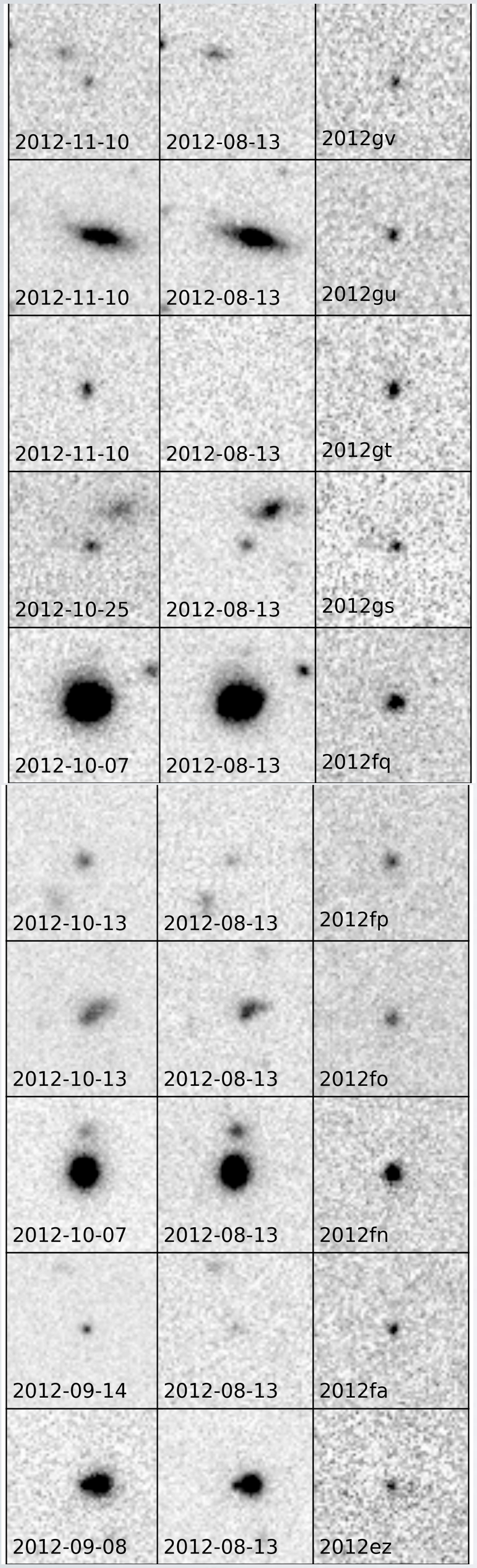
difference image



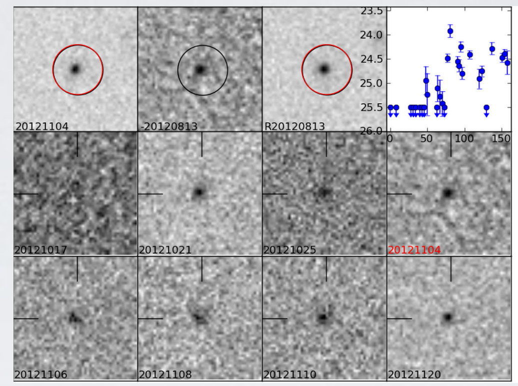


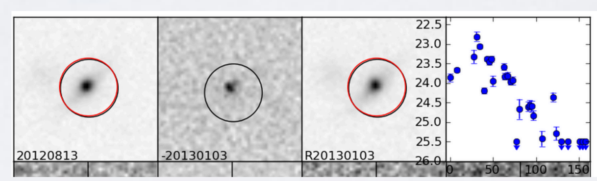
transient detection

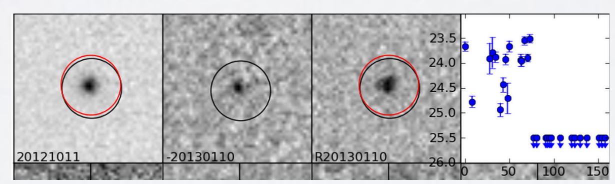
SNe

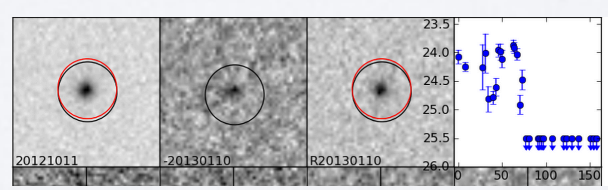


AGNs

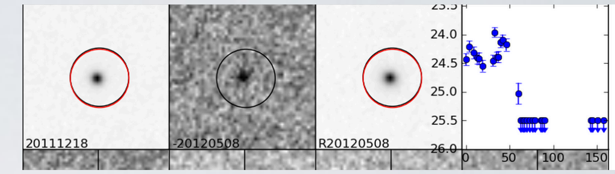




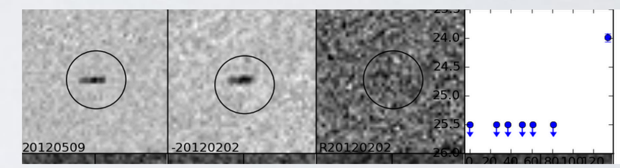




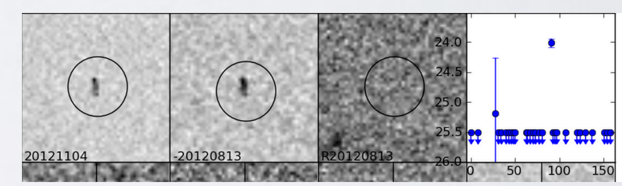
Variable stars



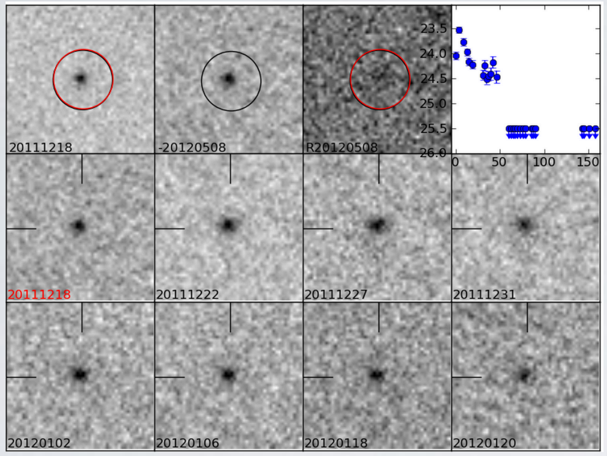
Moving objects

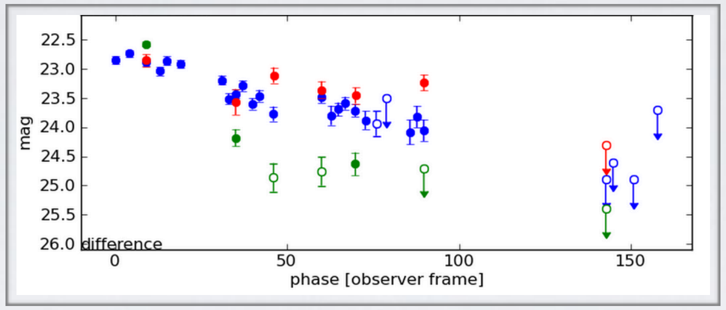


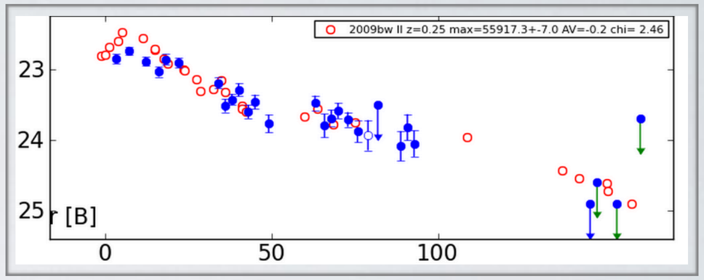
Spurious detection

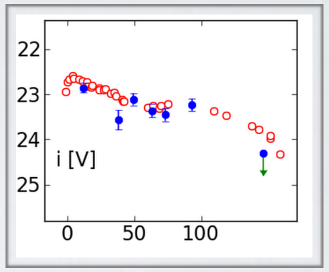


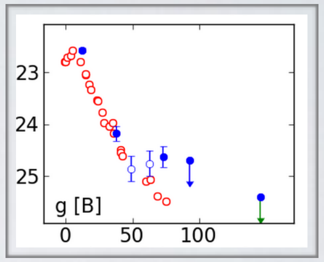
photometric typing

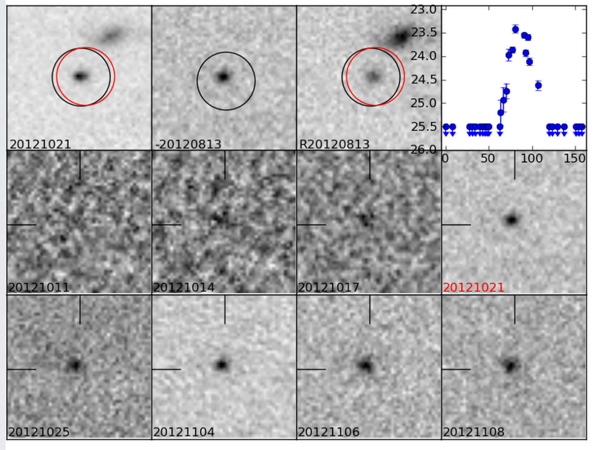


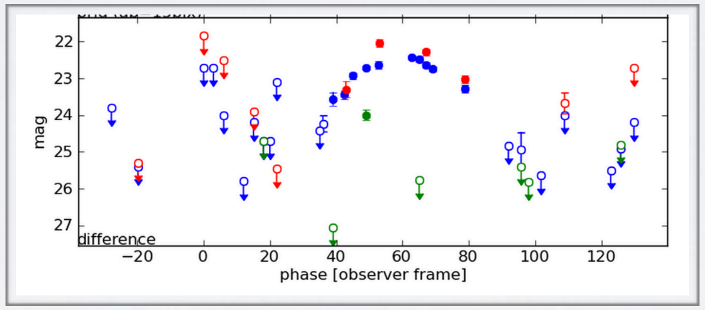


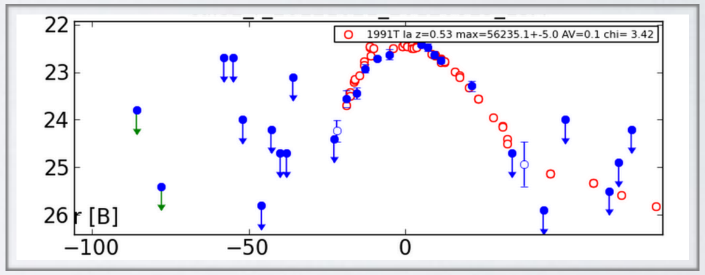


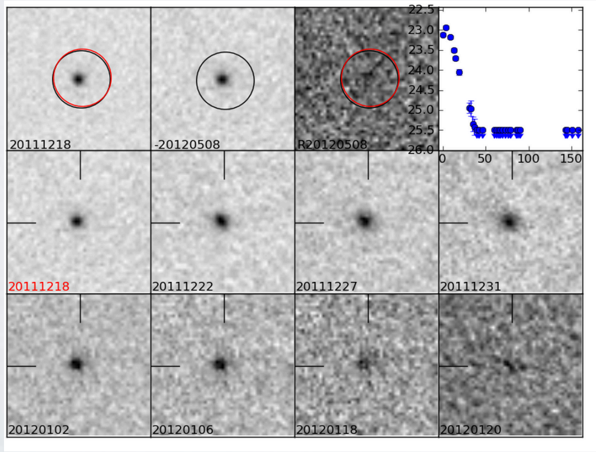


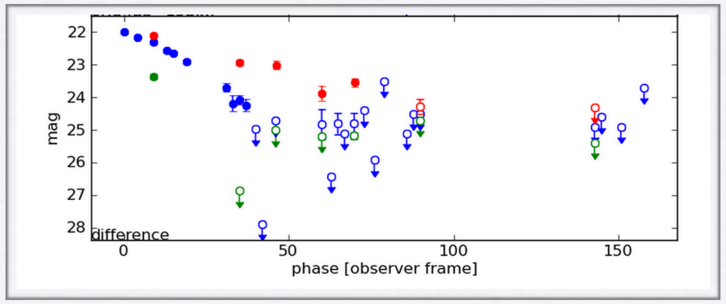


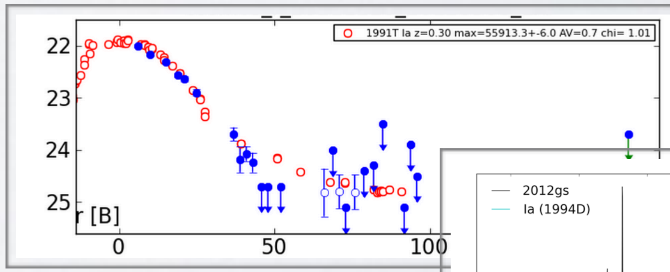


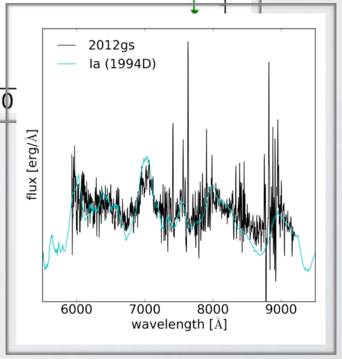








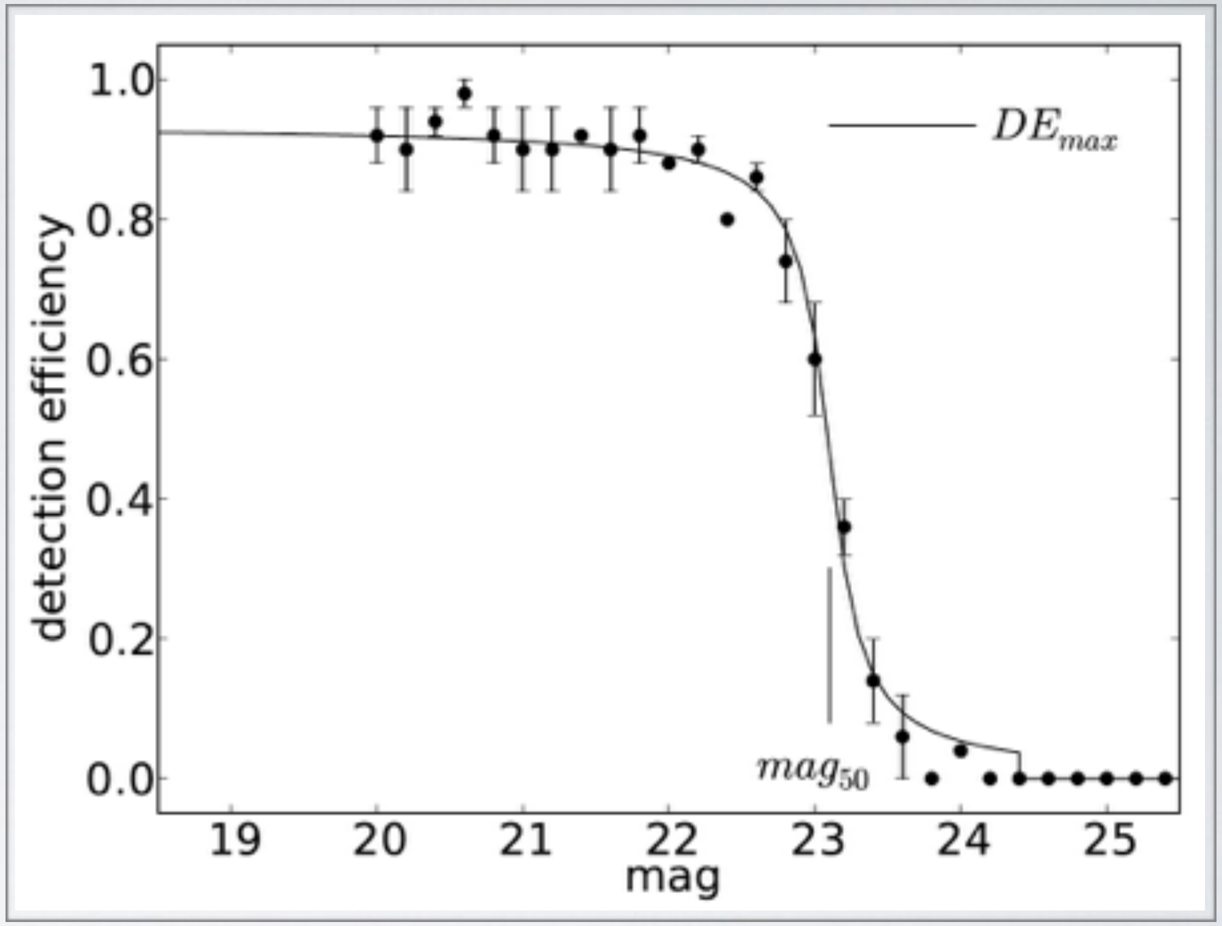




Detection Efficiency

artificial star experiments with range of magnitudes and positions on images

500 fake stars per image



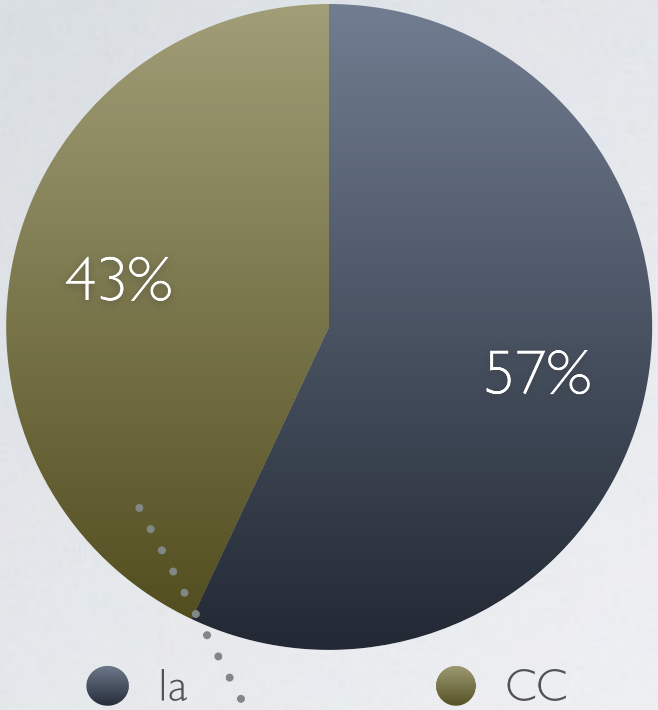
three different criteria to position the fake stars

- *events associated with galaxies*
- *event that coincide with persistent point like sources*
- *events with no counterpart in the template image*

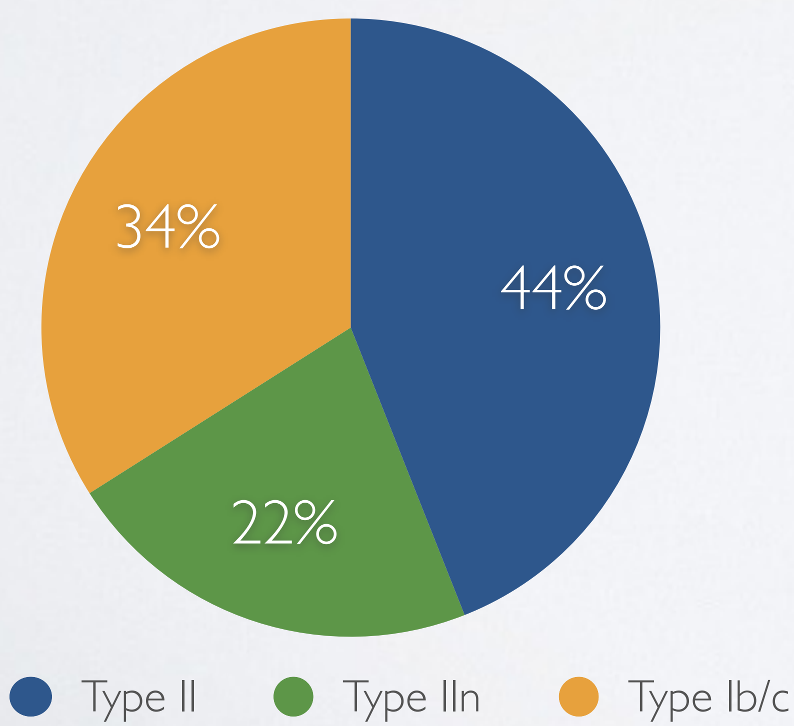
percentage detected/injected events → **detection efficiency**

SN sample

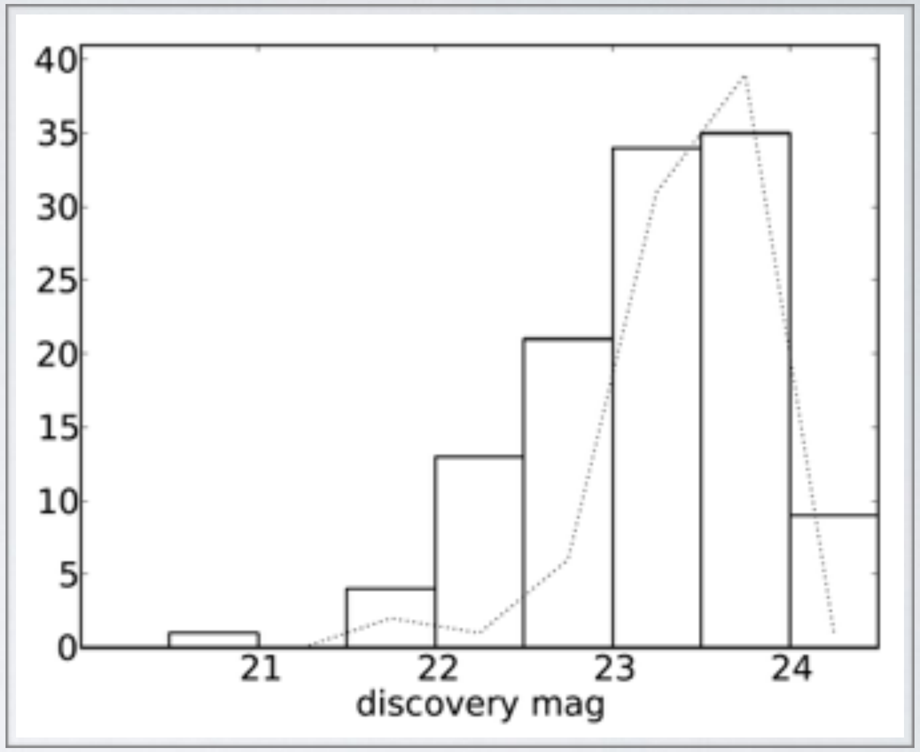
117 SNe



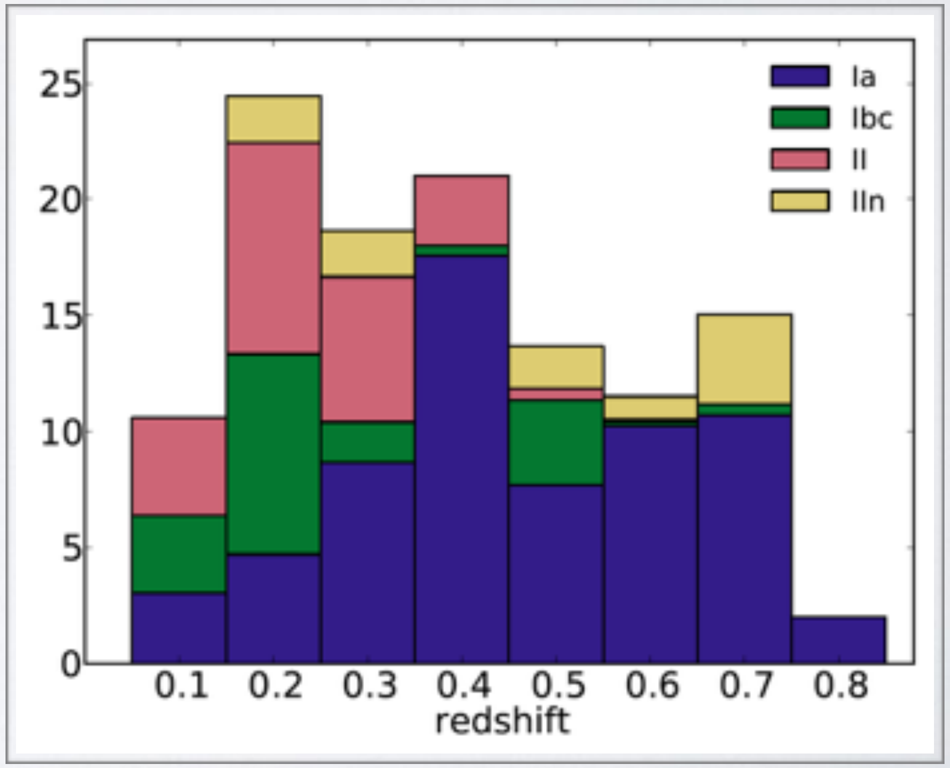
Core Collapse



r-band mag at discovery

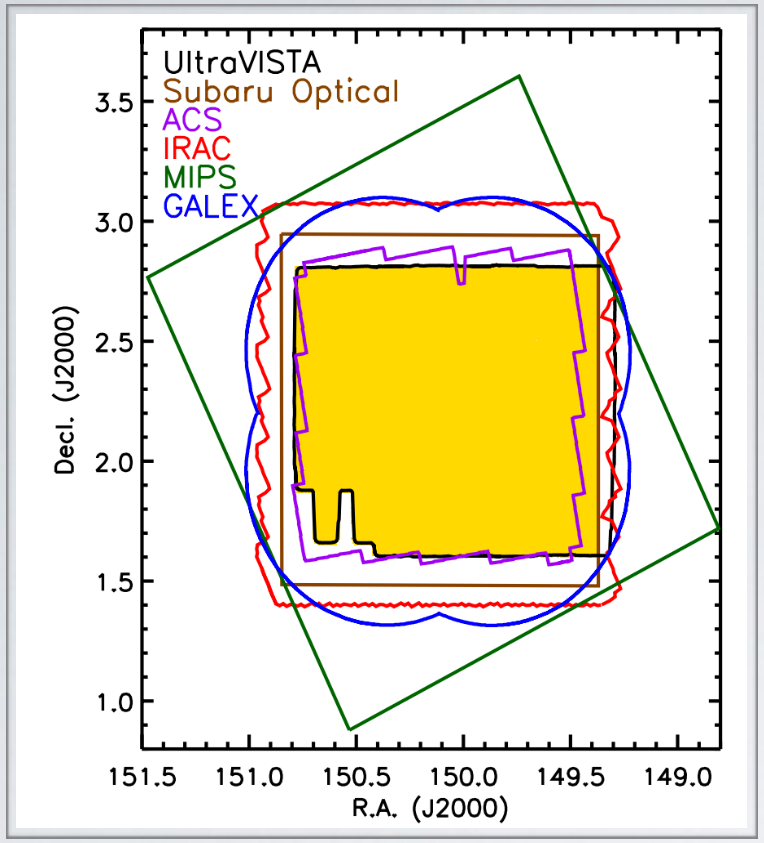


z distribution



Galaxy sample

COSMOS



1 deg^2

galaxy catalog obtained from

UltraVISTA survey

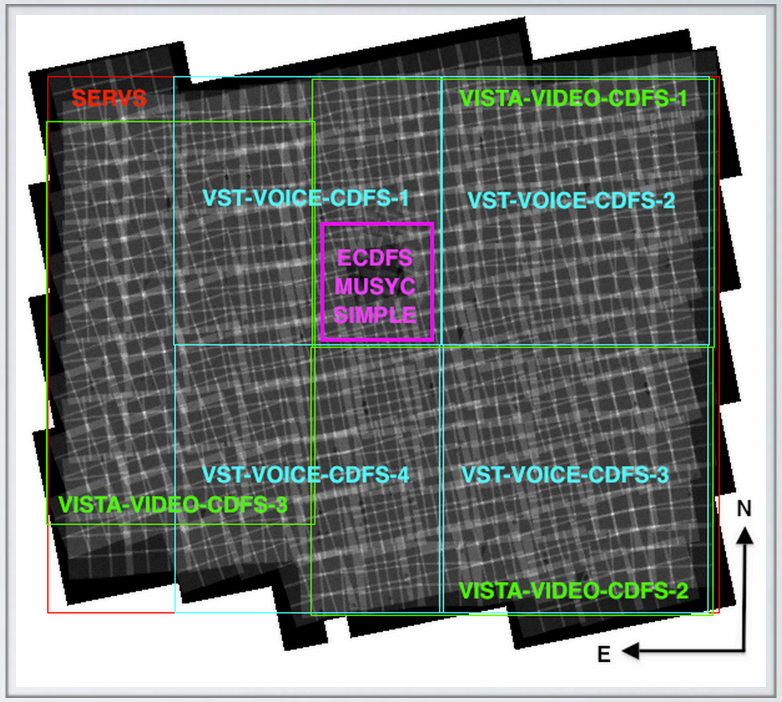
30 bands

GALEX, Subaru/SupremeCam, VISTA/VIRCAM, Spitzer/IRAC, MIPS

Muzzin+2013

$0 < z < 1$

CDFS



VOICE-CDFS 4 deg^2

g, r, i - SUDARE, P.I. Cappellaro - INAF GTO
u - VOICE, P.I. Covone & Vaccari - INAF GTO
J, H, K - VIDEO P.I. Jarvis
FUV, NUV - GALEX
IRAC - Spitzer CDFS 1,2

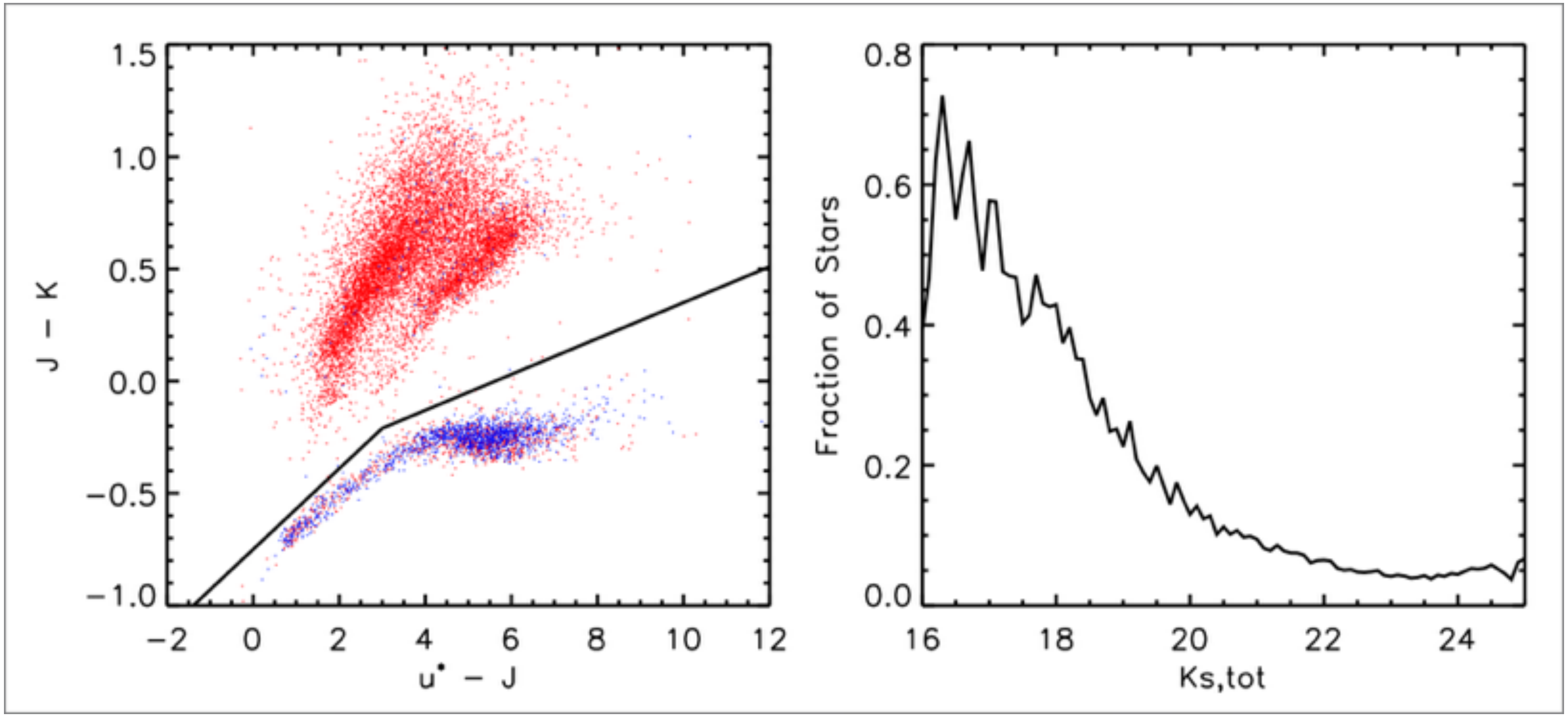
12 bands

source detection & photometry → SExtractor

photometric **z** → EAZY

SFR, sSFR, & Mass → FAST

Star vs. Galaxy



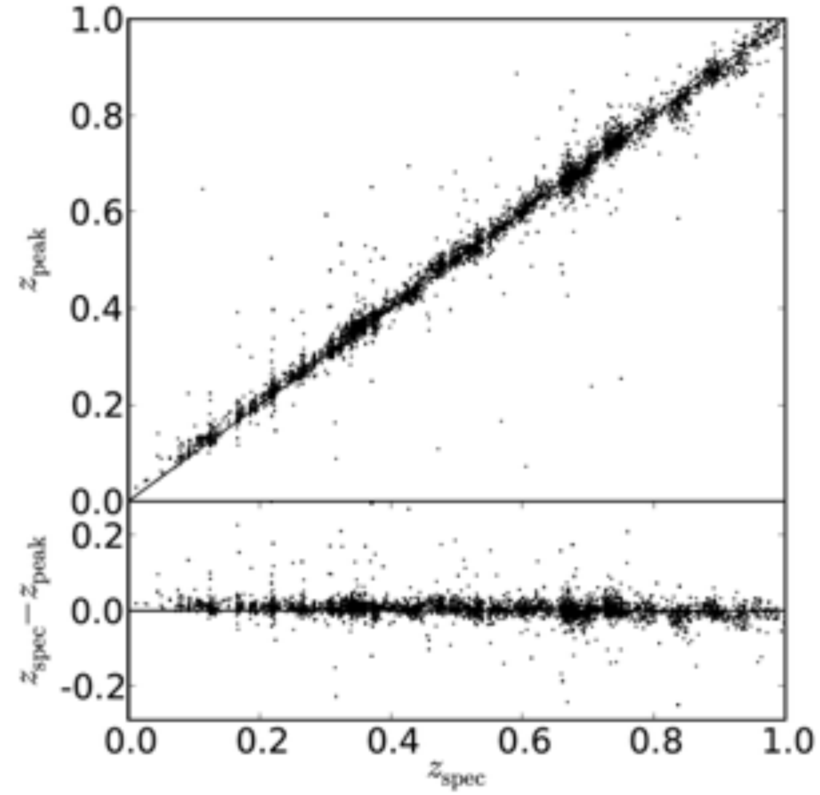
$$J - K > 0.18 \times (u - J) - 0.75 \qquad \text{for } u - J < 3.0$$

$$J - K > 0.08 \times (u - J) - 0.45 \qquad \text{otherwise.}$$

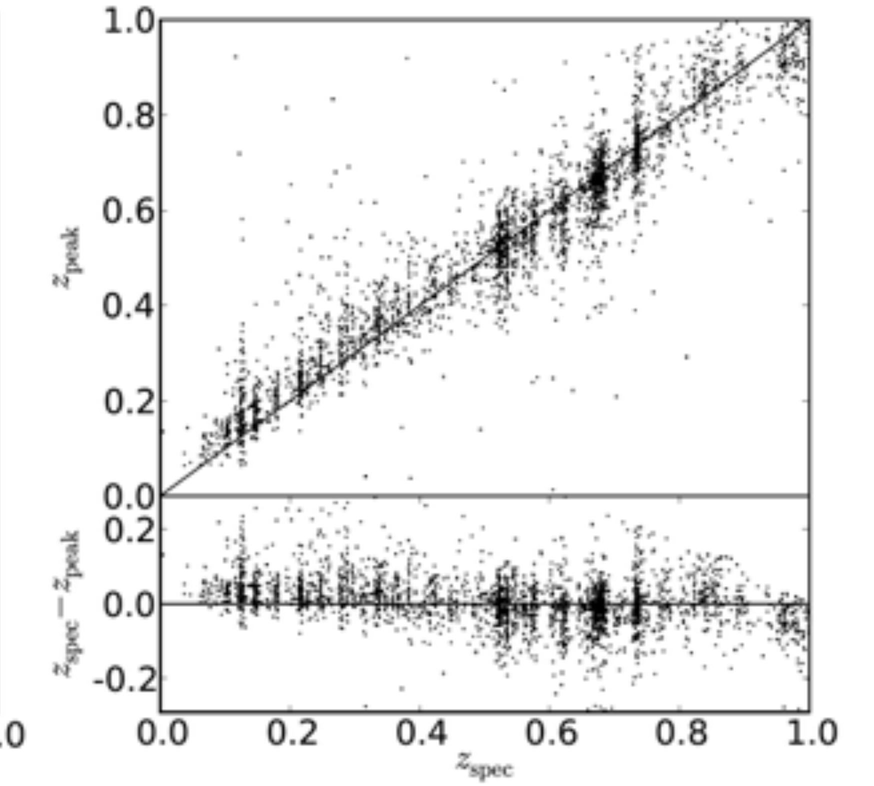
Brammer+2008
Muzzin+2013

Photometric z

COSMOS



CDFS

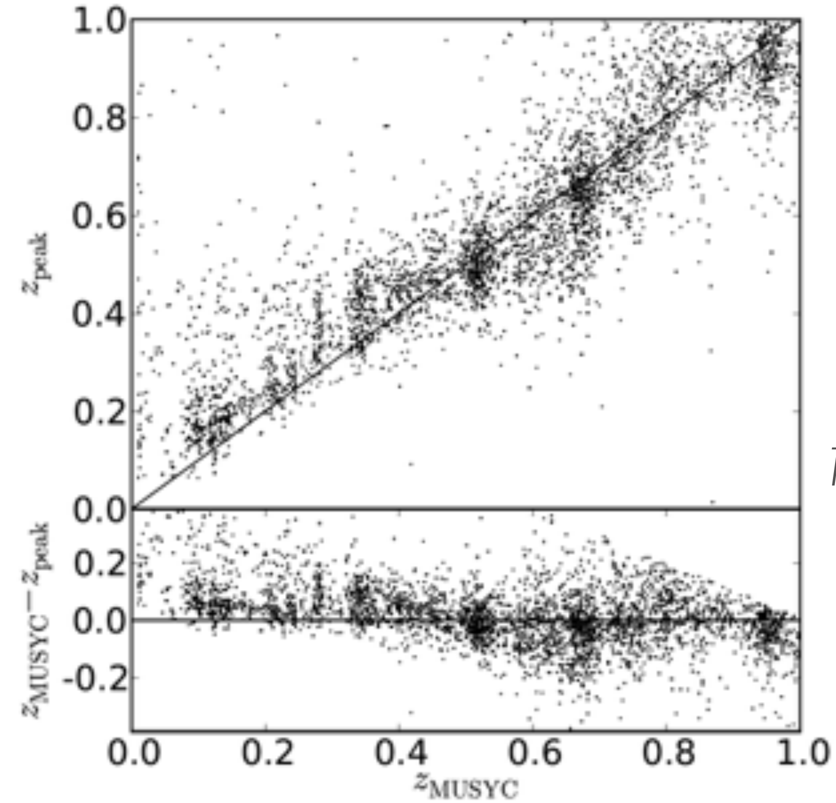


after removing outliers ~14% rms=0.02

methods to asses the quality of photo z

- *analyse width of CI and quality measurements*
- *comparing with different z estimates*
- *comparing with available spectroscopic z*

CDFS vs. MUSYC



5 sigma outlier fraction of 10%

spectroscopic z

COSMOS 4377 galaxies
CDFS 3362 galaxies

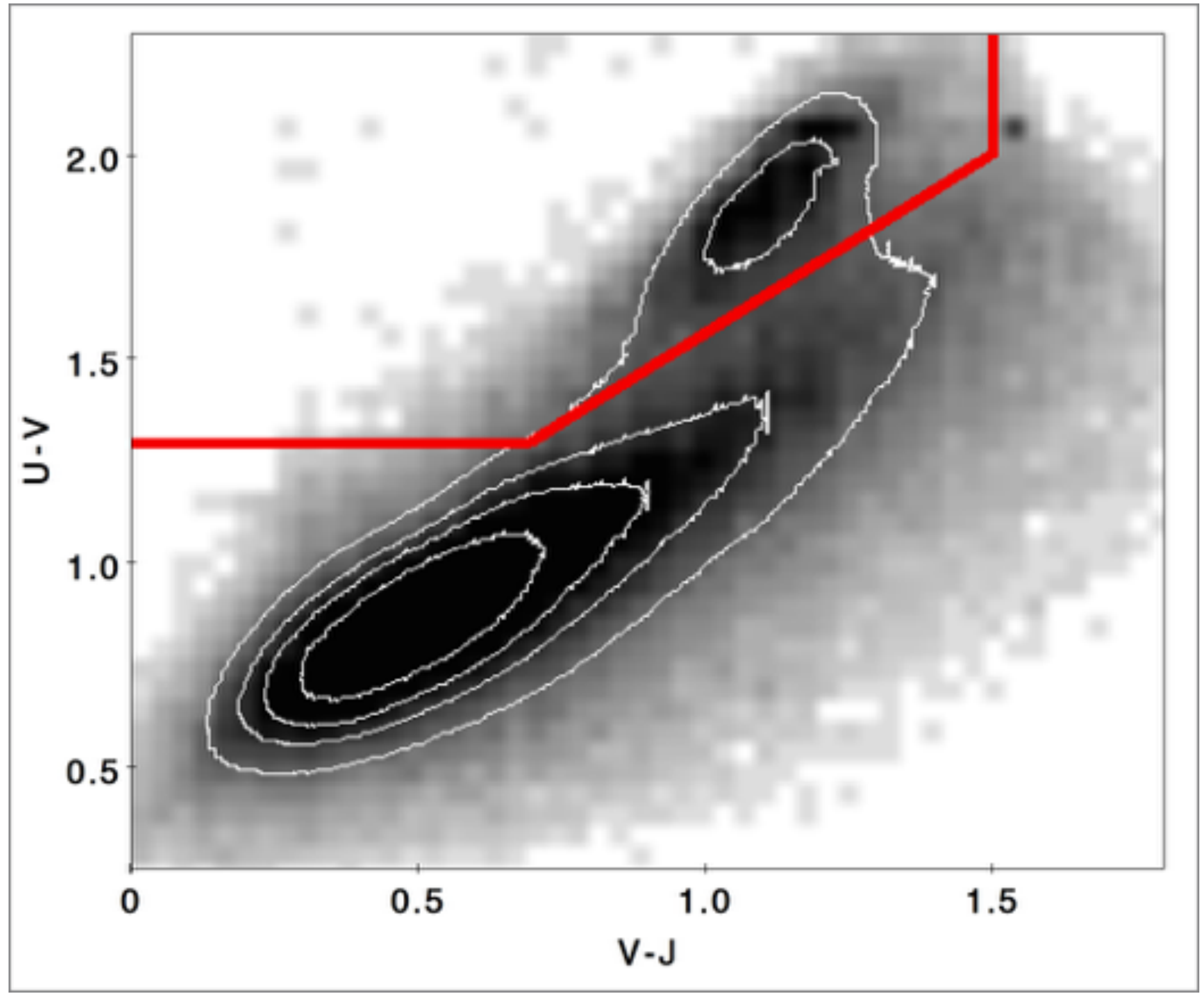
Multiwavlenght Survey by Yale-Chile

Cardamone+2010

Star forming & Passive galaxy separation

U-V Balmer break

V-J "red" passively evolving
from "red" dusty SF



$$U - V > 1.3 \qquad V - J < 1.5 \quad \text{at all redshifts}$$
$$U - V > (V - J) \times 0.88 + 0.69 \qquad \text{for } 0 < z \leq 1$$

Williams+2009

Control Time & SN rates

Control Time(CT)-the effective observing time

Zwicky 1942

CT depends on SN luminosity and light-curve evolution

total CT of a campaign is the sum of CT for each observation

Cappellaro+1997

Ia, Ib/c, II, IIn & SLSN considered separately

simulate a number N of events that explore the possible epochs of explosion:

detection probability

$$CT_{\mathrm{SNi},E_{BV}}(z) = (t_K - t_0 + 365)\frac{\sum_{j=1}^{N} p(x_j)}{N}$$

last observation epoch

first observation epoch

$$CT_{\mathrm{SN}}(z) = \sum_{\mathrm{SNi}} \sum_{\mathrm{E_{BV}}} f_{\mathrm{SNi}}\, g_{\mathrm{E_{BV}}}\, \mathrm{CT}_{\mathrm{SNi,E_{BV}}}(z);$$

subtype fraction

distribution of colour excess E(B-V)

SN rate per unit volume

redshift range: 0 < z < 1

volumetric SN rates per z bin:

number of SN of a given type

$$\boxed{r_{\mathrm{SN}}(z) = \frac{(1+z)}{V(z)} \frac{N_{\mathrm{SN}}(z)}{CT_{\mathrm{SN}}(z)}}$$

control time

comoving volume

$$V(z) = \frac{4\pi}{3} \frac{\Theta}{41\,253} \left[\frac{c}{H_0} \int_{z_1}^{z_2} \frac{\mathrm{d}z'}{\sqrt{\Omega_{\mathrm{M}}(1+z')^3 + \Omega_\Lambda}} \right]^3 \mathrm{Mpc}^3,$$

in the frames of
standard cosmological model

z is the midpoint of z bin $z_1 - z_2$

CC SN rate as a function of cosmic time

relation of CC SN rates and current SFR:

SFR

$$r_{\rm CC}(z) = K_{\rm CC} \times \psi(z)$$

number of stars that produce CCSNe:

$$K_{\rm CC} = \frac{\int_{m_{\rm L,CC}}^{m_{\rm U,CC}} \phi(m){\rm d}m}{\int_{m_{\rm L}}^{m_{\rm U}} m\phi(m){\rm d}m}$$

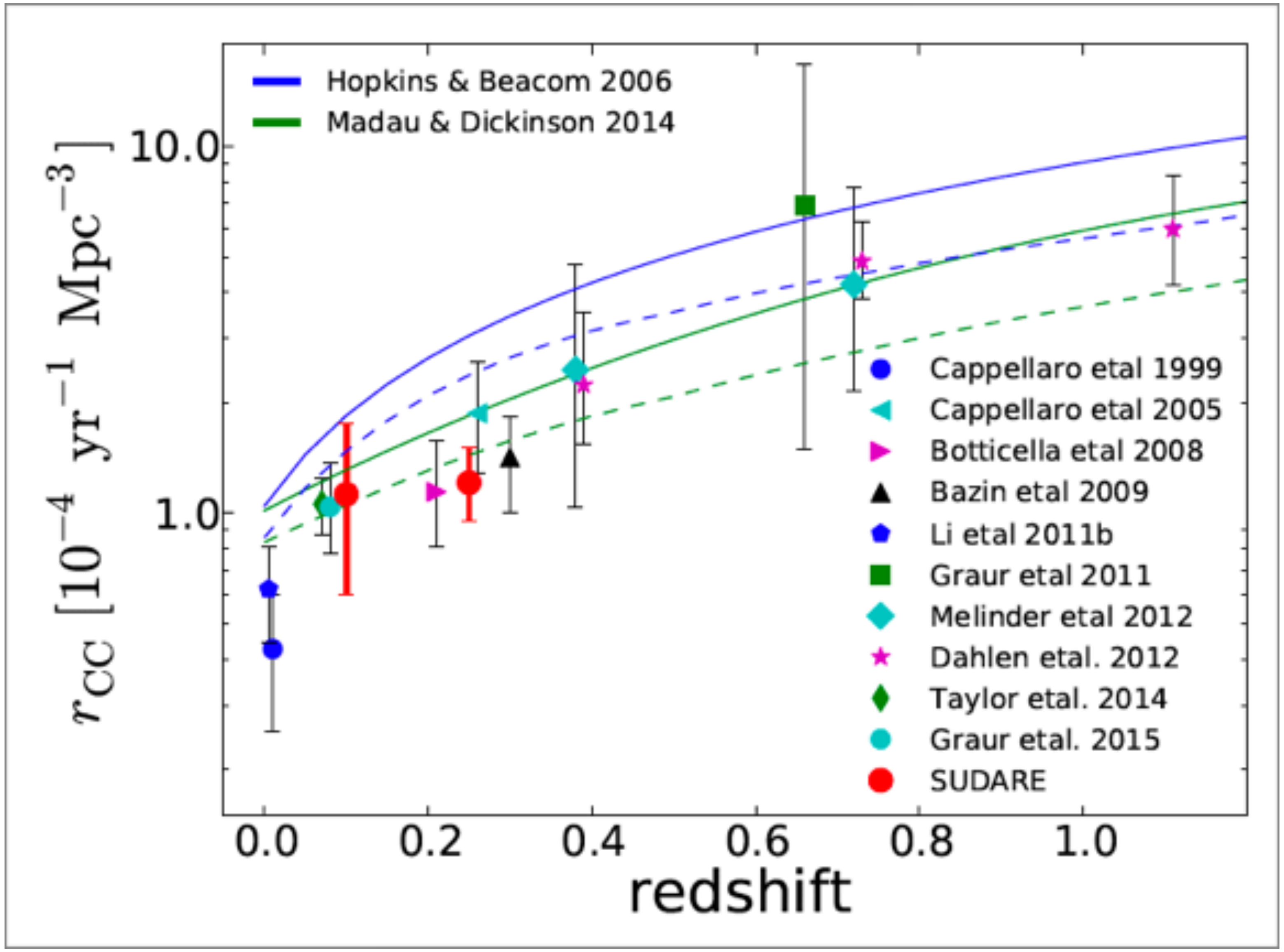
predicted rates from SFH:

Madau & Dickenson 2014
Hopkins & Bacon 2006

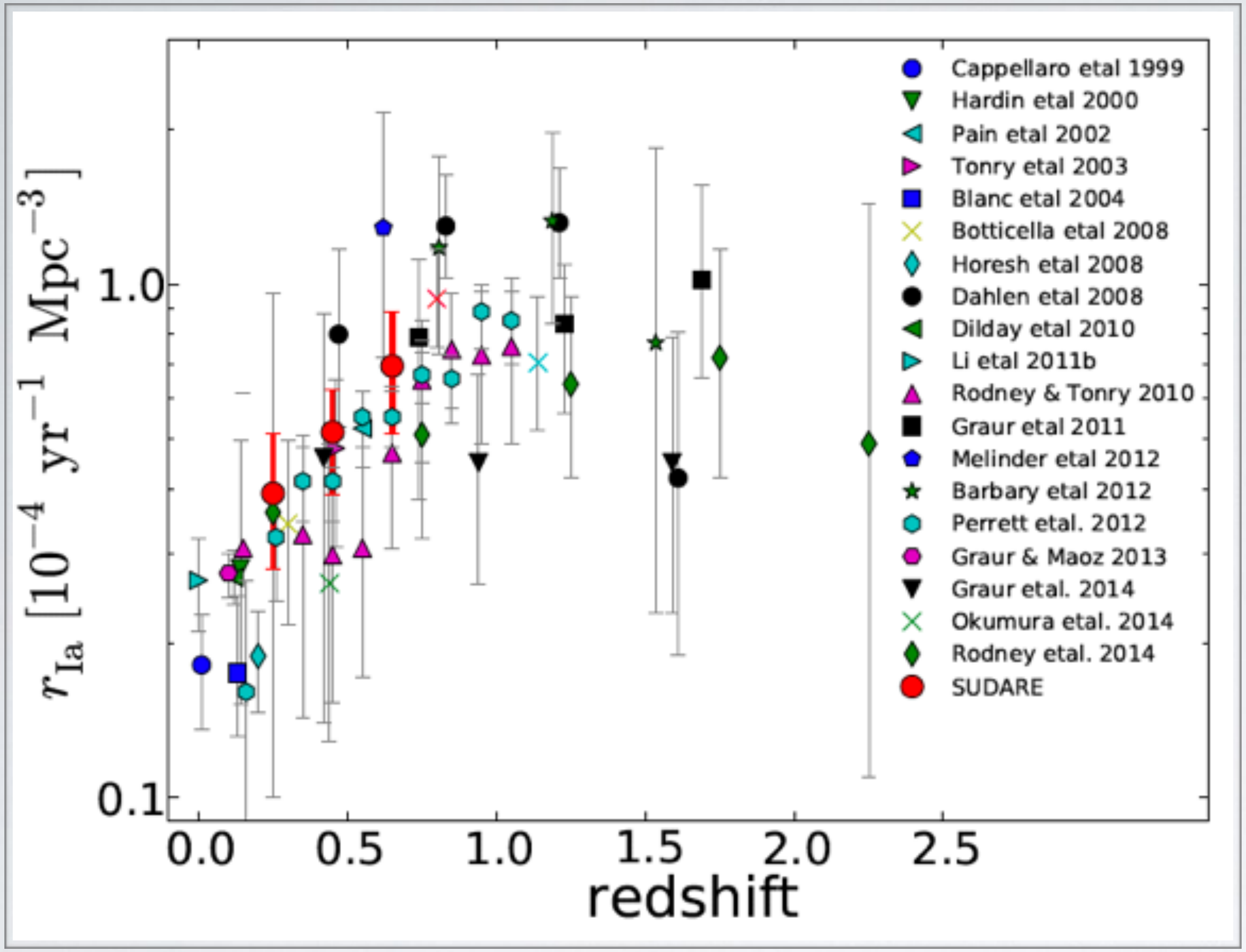
Mannucci+2007, Matila+2012

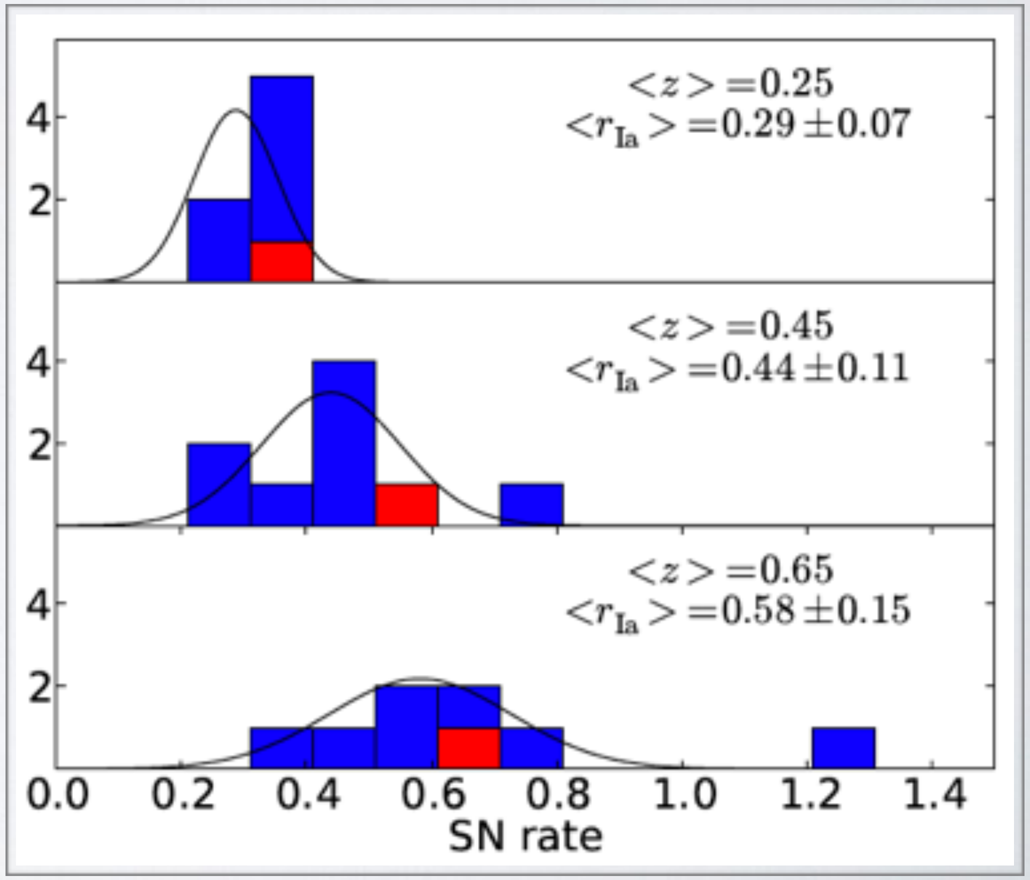
measurements do not account for the correction of hidden SNe

null value suggest 1SLSN for each 500 CCSNe



Ia SN rate as a function of cosmic time





Ia SNe rates compared with models

SD, SD1,DDC & DDW

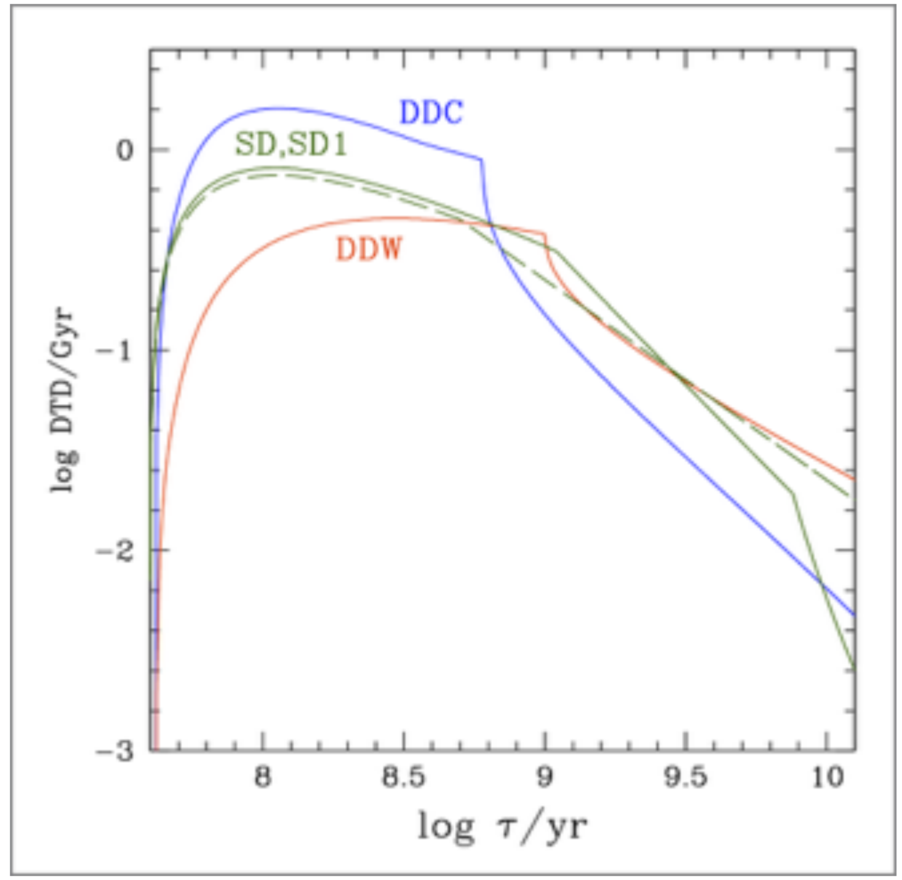
expected evolution from models:

DTD

$$r_{\mathrm{Ia}}(t) = K_{\mathrm{Ia}} \int_{\tau_i}^{\min(t,\tau_x)} f_{\mathrm{Ia}}(\tau)\psi(t-\tau)\mathrm{d}\tau$$

number of Ia progenitors

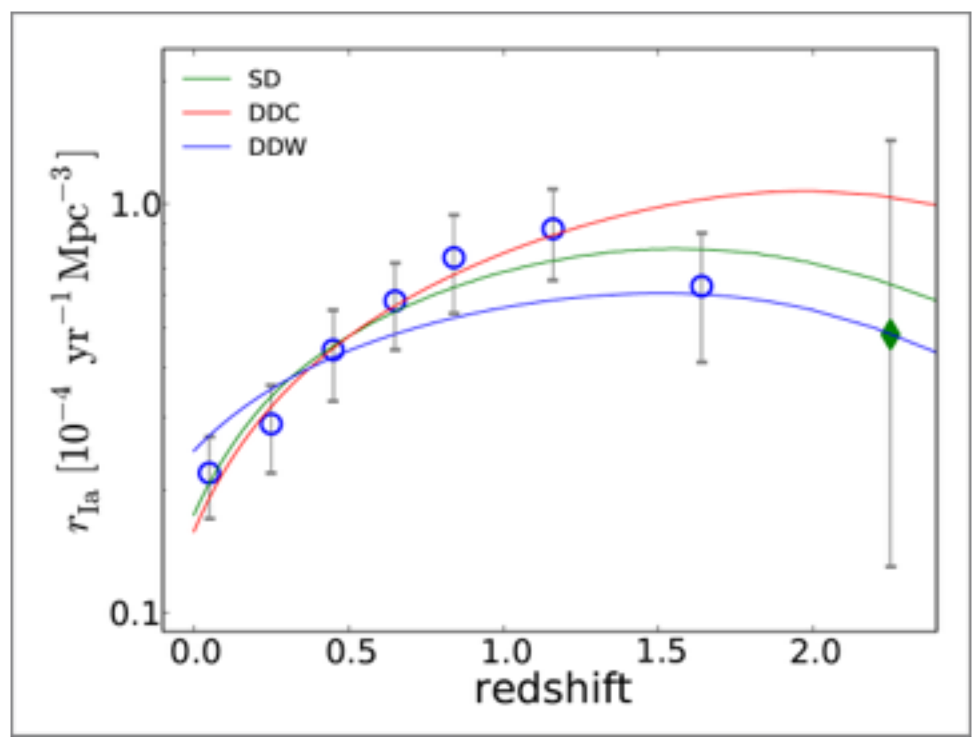
SFR



Greggio 2010

Maoz+2011

Greggio 2005



$DDC\ -\ t^{-1.3}$

$DDW\ -\ t^{-0.8}$

adopted SFH model

Madau & Dickenson 2014

z > 2 *from*

Rodney+2014

SN rates as a function of galaxy colour

van den Bergh 1990
Della Valle & Livio 1994

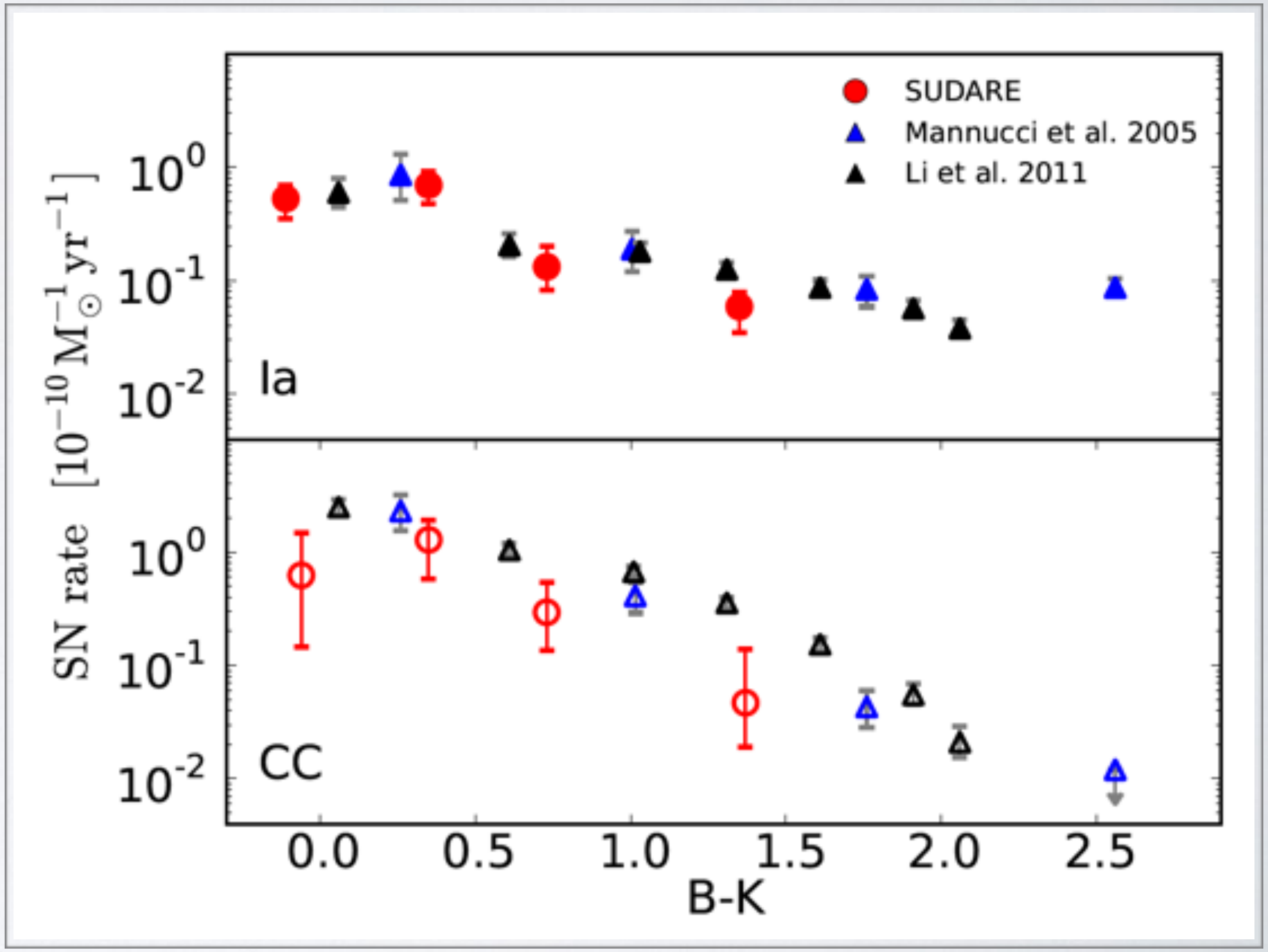
in late types SN Ia rate is higher
than in early types

“blue” galaxies exhibit 30 times higher Ia rates than that of “red”

Mannucci+2005

Ia 0.15 < z < 0.75
CC 0.15 < z < 0.35

SN rates vs. B-K galaxy colour (AB mag)



SN rates in SF & passive galaxies

SN type	gal type	N_{SN}	rate
Ia	passive	4.0	$0.5^{+0.2}_{-0.3}$
	star-forming	32.6	$2.7^{+0.5}_{-0.4}$
CC	passive	0.0	< 0.1
	star-forming	13.6	$4.4^{+1.2}_{-1.3}$

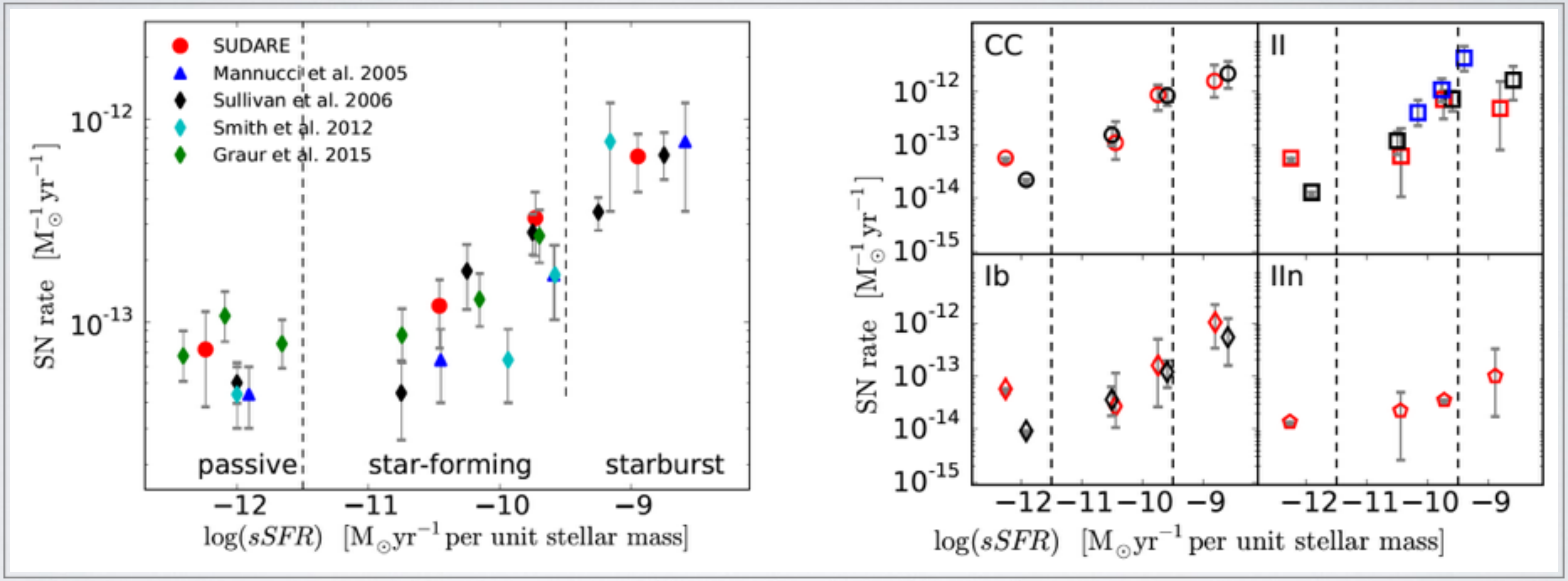
Ia SN rate a factor of ~4 higher in SF over passive galaxies

CC SN rate order of mag higher in SF over passive galaxies

SN rates as function of sSFR

divided into 3 groups

zero mean SFR
-12 < log(sSFR) < -9.5
log(sSFR) > -9.5

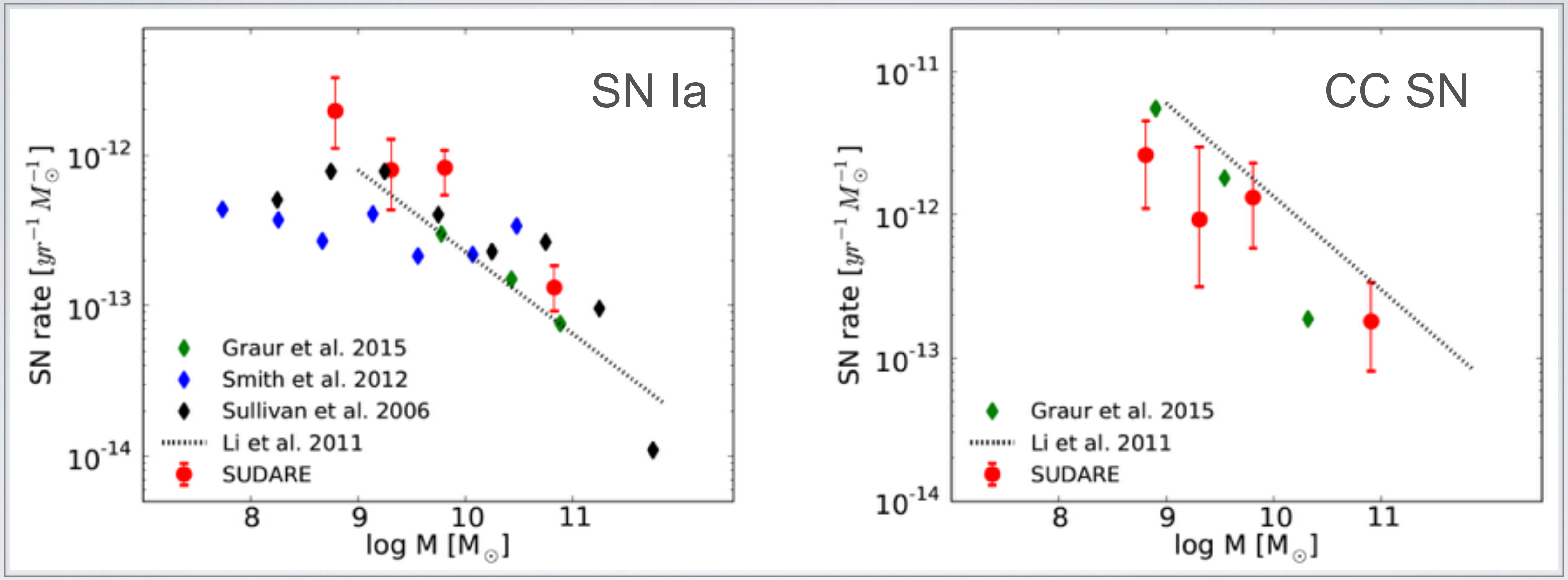


Sullivan+2006

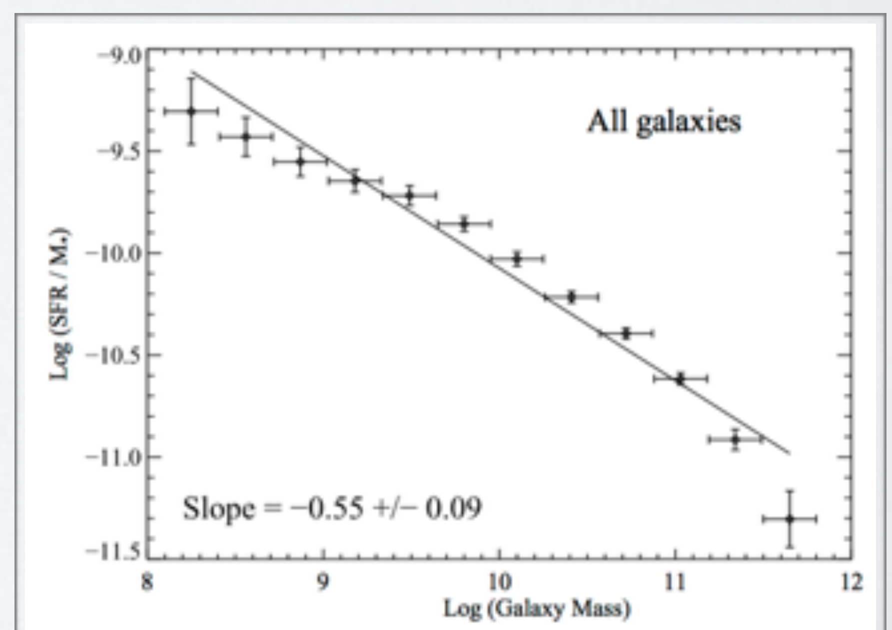
factor 5 increase for Ia
factor 15 increase for CC

SN rates as a function galaxy mass

in the SF
galaxy sample



dose not seem to vary
with redshift



Li+2011

Work in progress…

SN rates as a function of galaxy radio & infrared power

SN rates in filed vs galaxy clusters

Harutyunyan+ in preparation

SN rates as a function of galaxy radio & infrared power

Della Valle+2005

Radio-loud & Radio Quite

$T \leq -1.5$

1.4GHz radio power

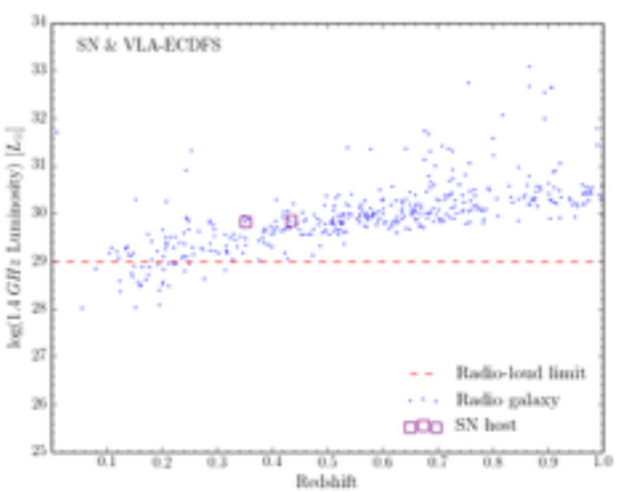
$> 10^{29} ergs\,s^{-1} Hz^{-1}$

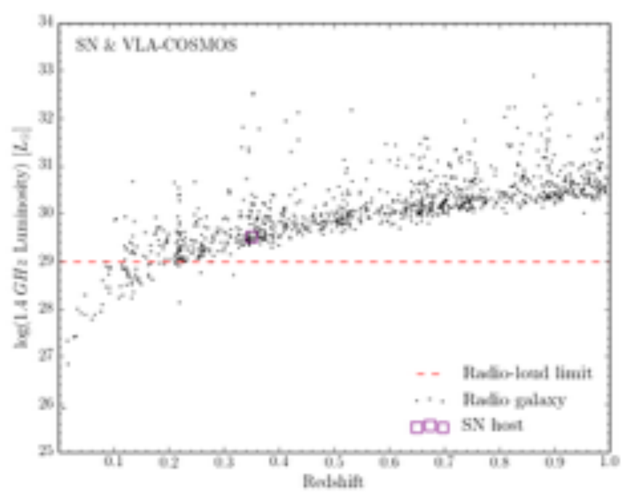
$< 4\times10^{27} ergs\,s^{-1} Hz^{-1}$

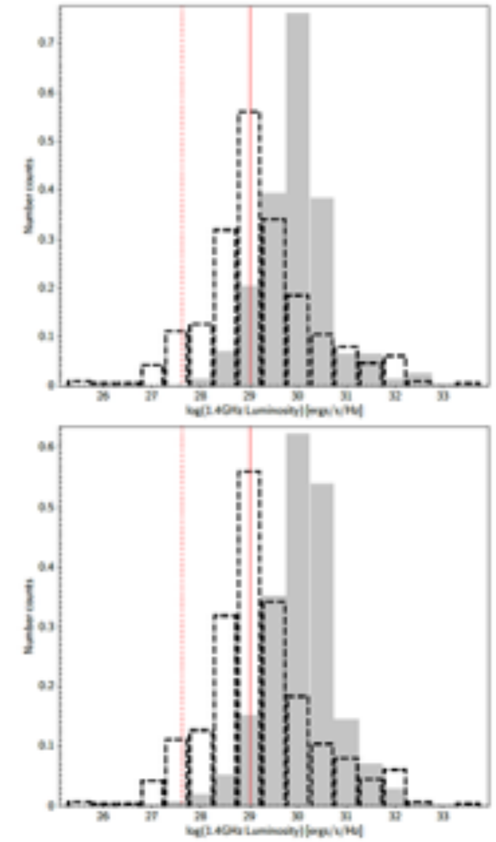
$+$

Radio-loudest

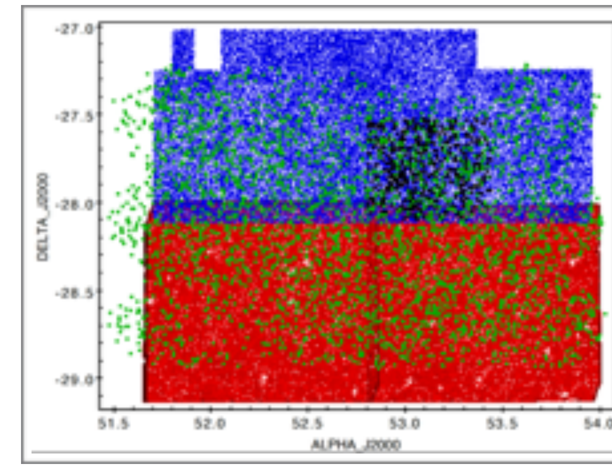
$> 10^{30} ergs\,s^{-1} Hz^{-1}$







CDFS 1, 2
CDFS 3, 4
VLA
ATLAS DR3



Radio-loud

COSMOS - Ic
CDFS - Ic, IIn

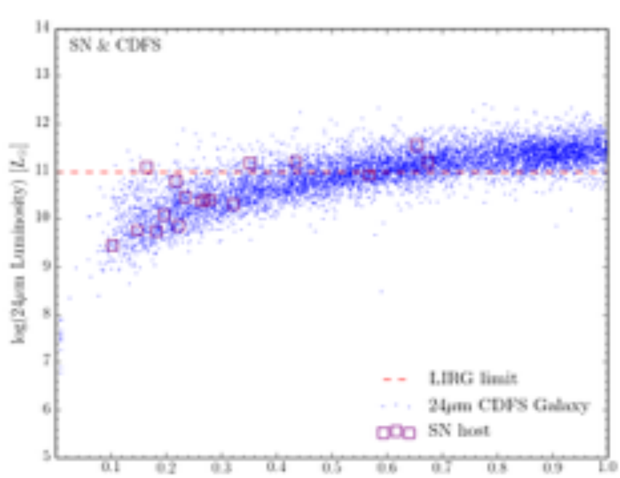
LIRG-loud

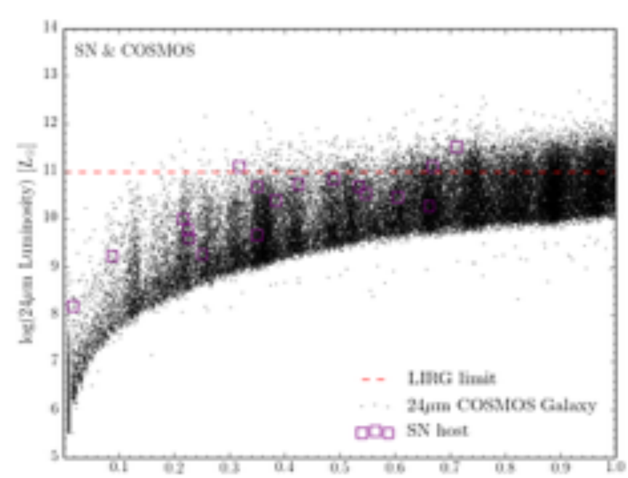
COSMOS - Ia, II, IIn
CDFS - 2 Ia, 2 IIn, Ic

BIRG & LIRG

$> 10^{10} L_\odot$

$> 10^{11} L_\odot$





Graham+2010

$0.1 < z < 0.6$

Harutyunyan+ in preparation

SN rates as a function of galaxy radio & infrared power

Della Valle+2005

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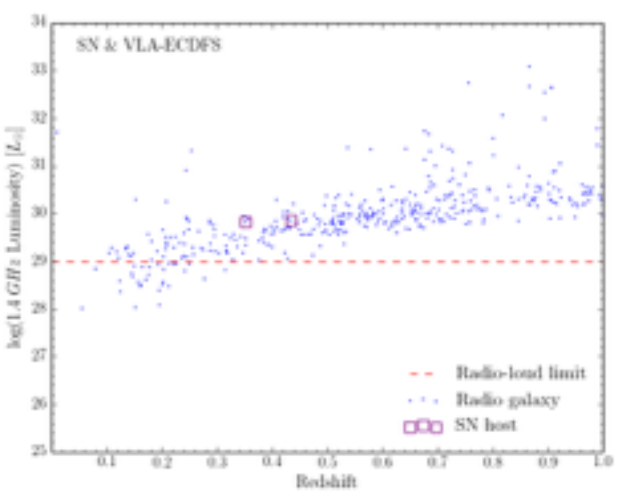

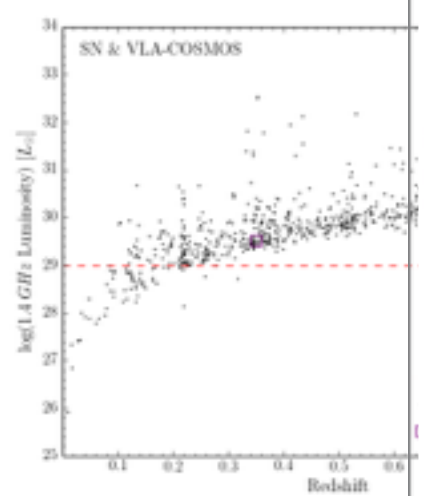

CDFS 1, 2
CDFS 3, 4
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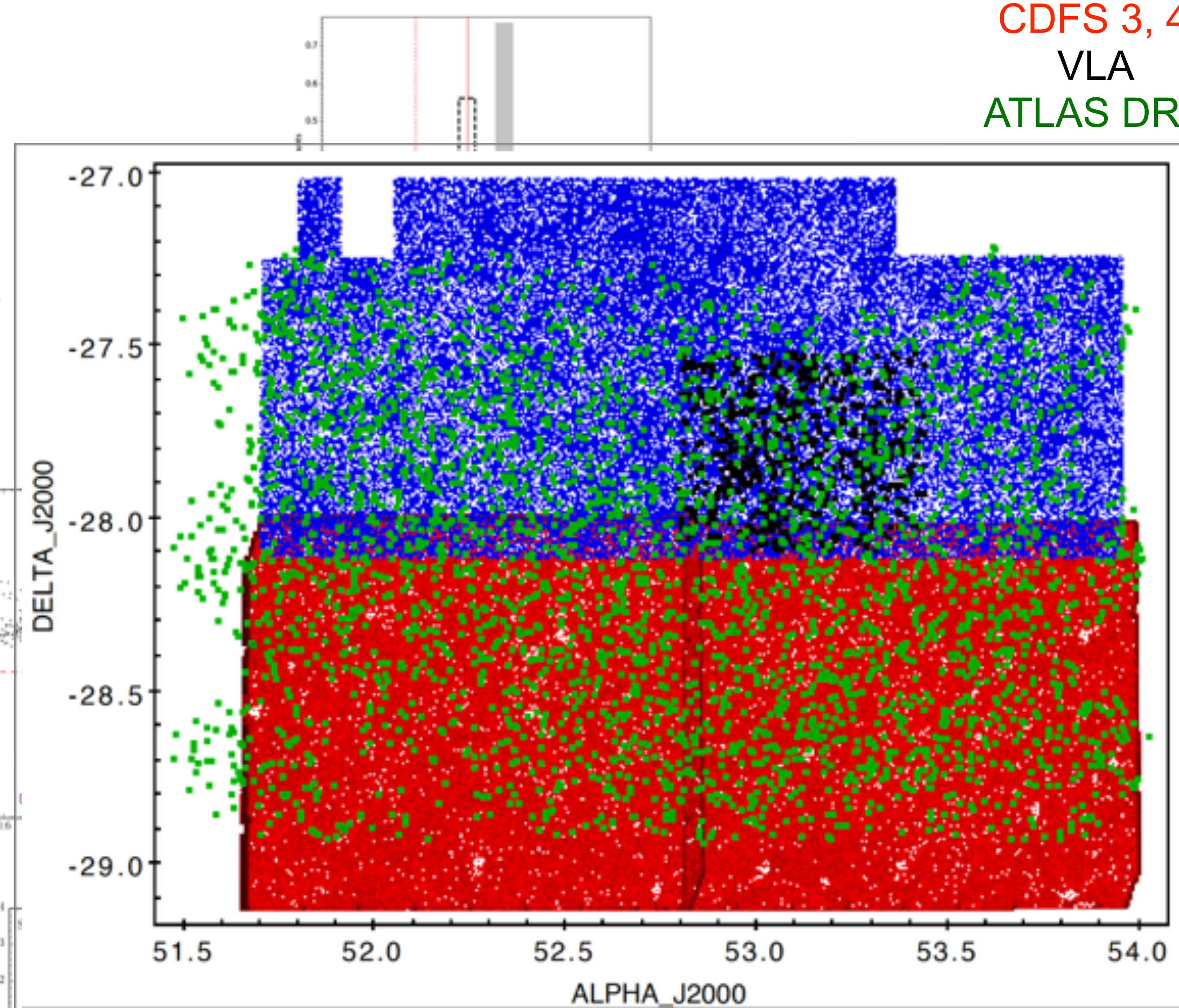
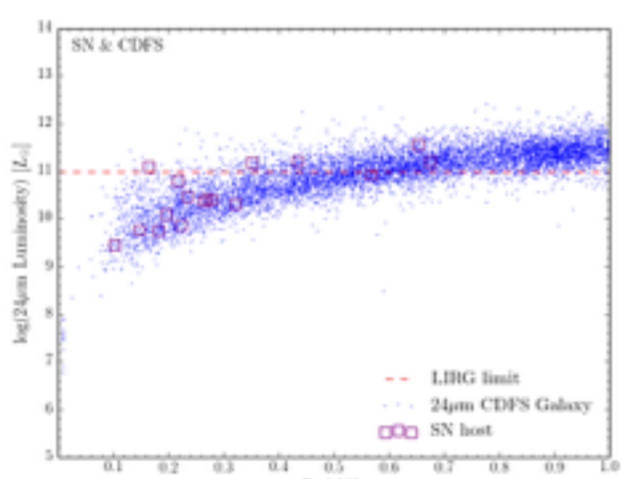
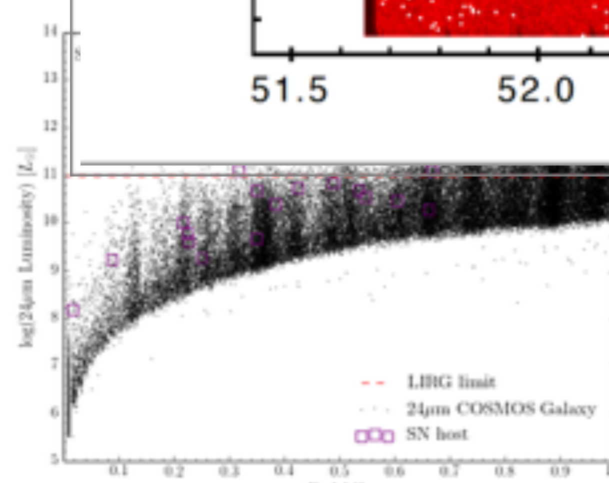


BIRG & LIRG

$> 10^{10} L_{\odot}$

$> 10^{11} L_{\odot}$





0.1 < z < 0.6

Harutyunyan+ in preparation

SN rates as a function of galaxy radio & infrared power

Della Valle+2005

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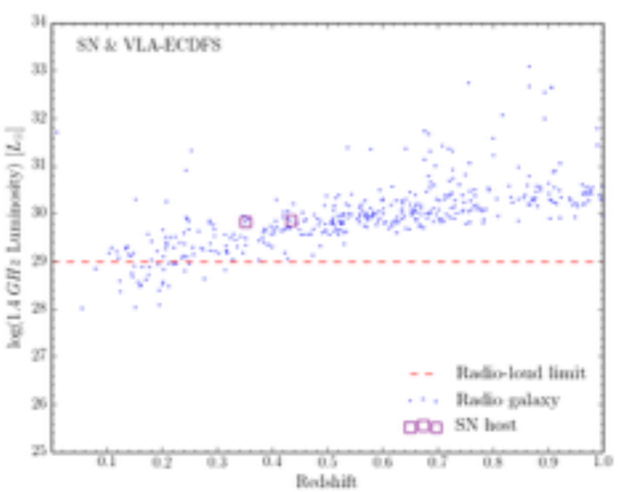

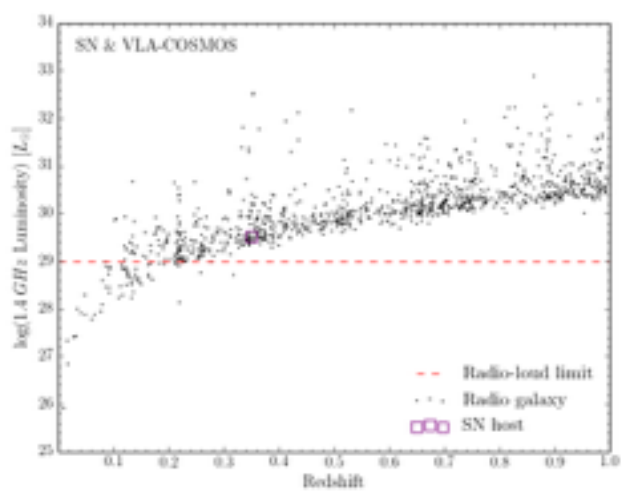

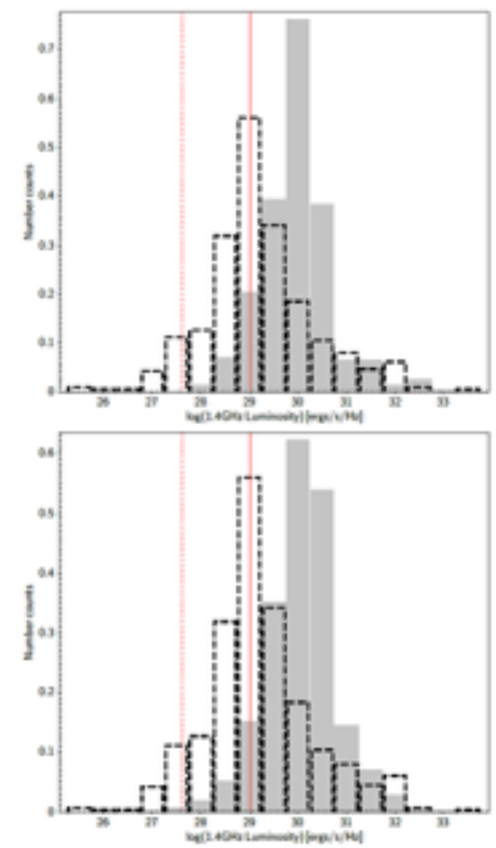

CDFS 1, 2
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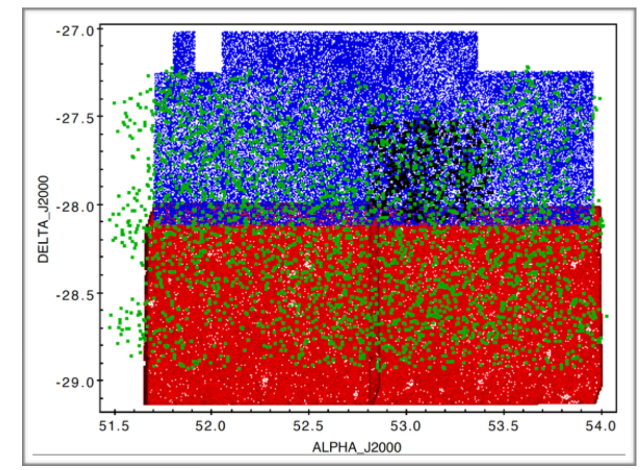
VLA
ATLAS DR3



Radio-loud

COSMOS - Ic
CDFS - Ic, IIn

LIRG-loud

COSMOS - Ia, II, IIn
CDFS - 2 Ia, 2 IIn, Ic

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$> 10^{10} L_\odot$

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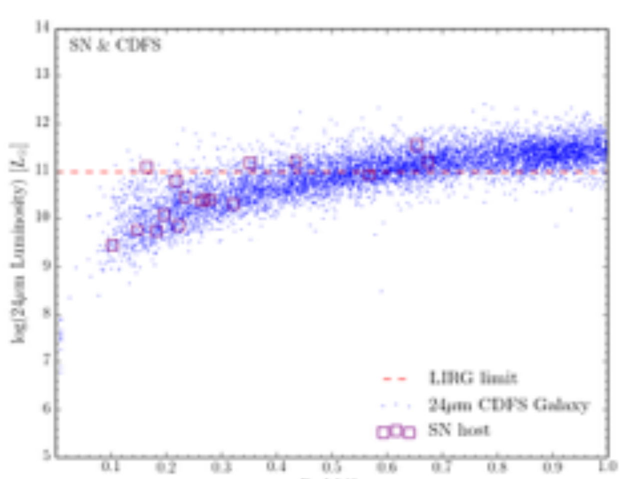

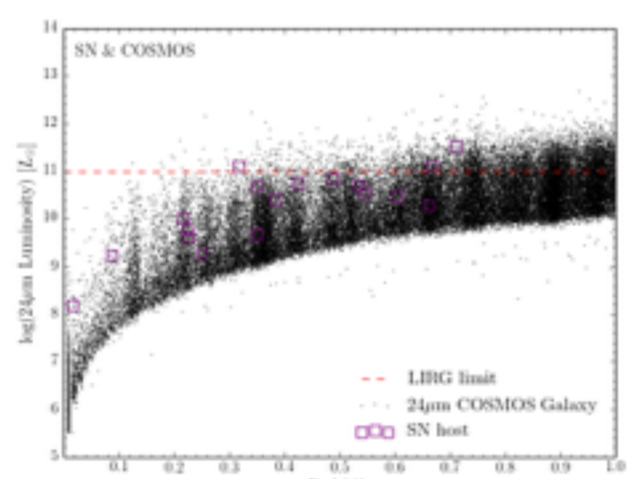

Graham+2010

$0.1 < z < 0.6$

Harutyunyan+ in preparation

SN rates as a function of galaxy radio & infrared power

Della Valle+2005

Radio-loud &
Radio Quite

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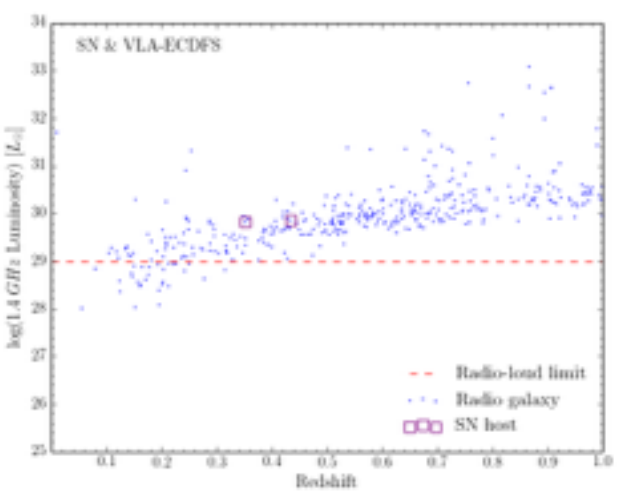
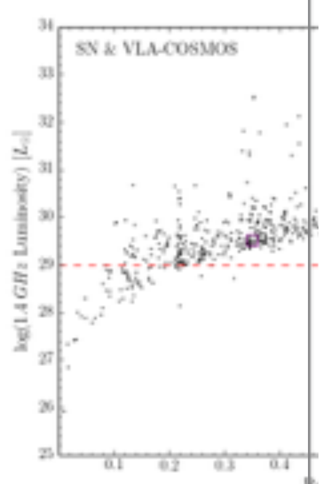
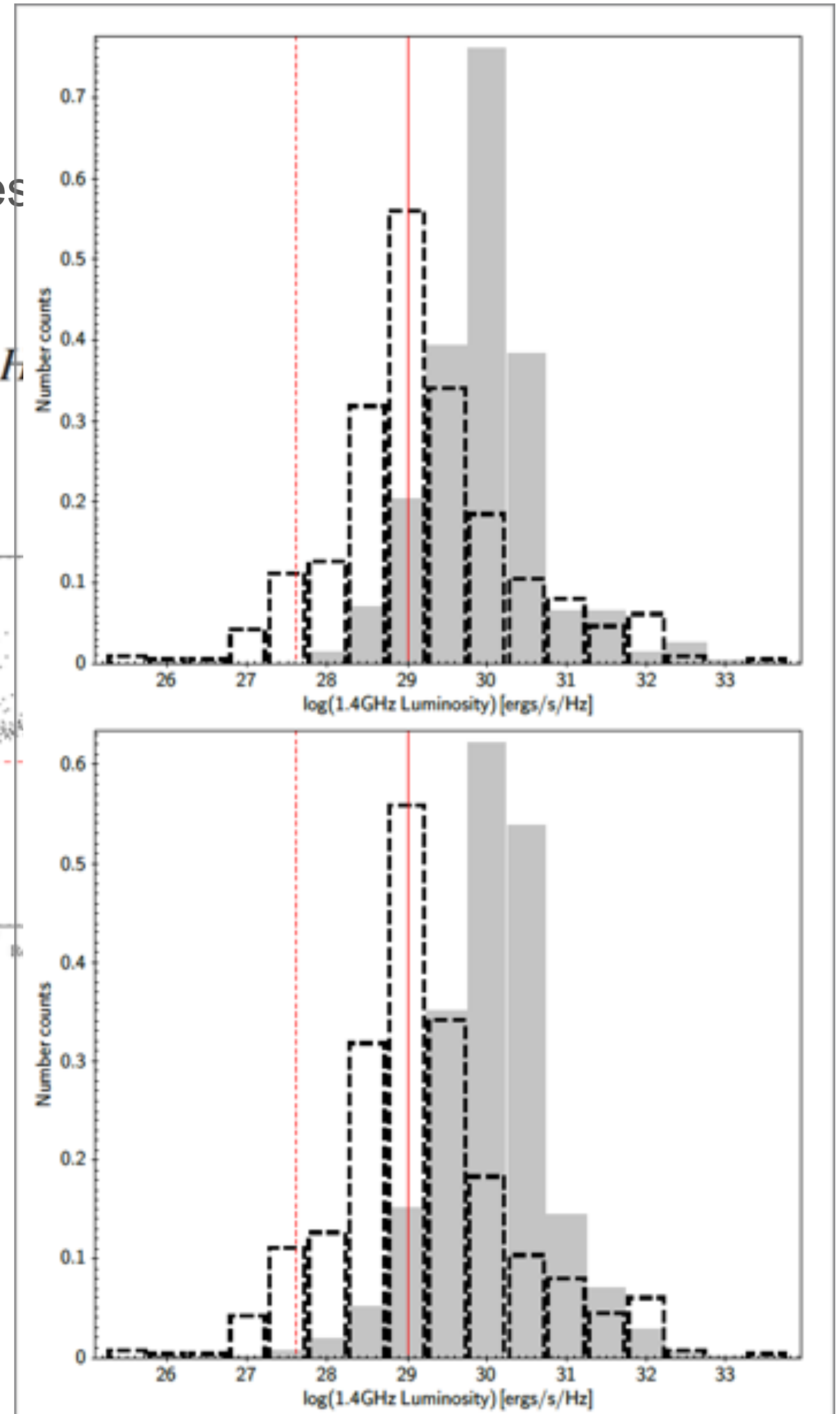
Radio-loudes

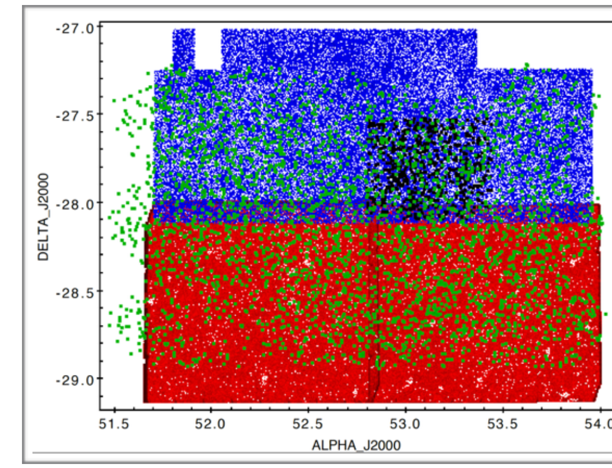
$+ \quad > 10^{30}\, ergs\, s^{-1}\, H$







CDFS 1, 2
CDFS 3, 4
VLA
ATLAS DR3



BIRG & LIRG

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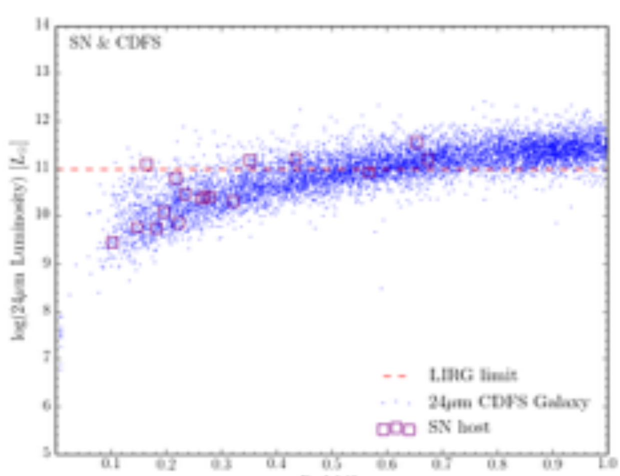

LIRG-loud

COSMOS - Ia, II, IIn
CDFS - 2 Ia, 2 IIn, Ic

Graham+2010

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Radio-loudest

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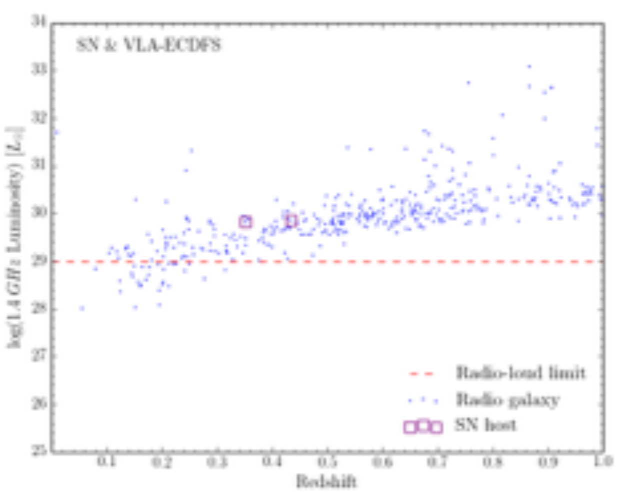
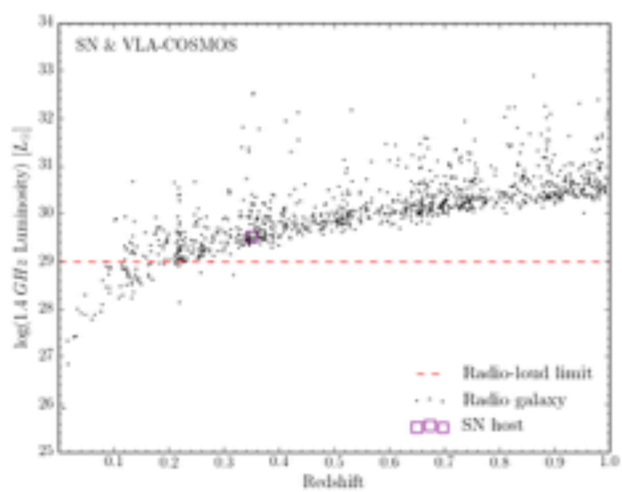
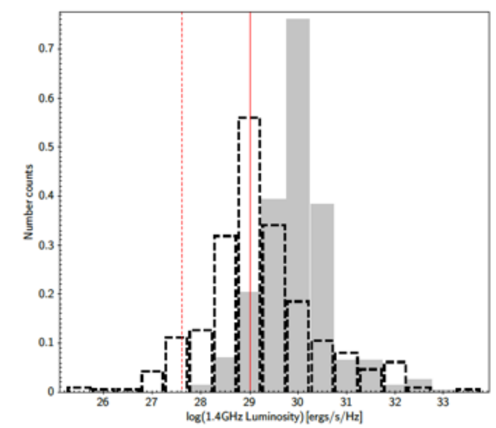
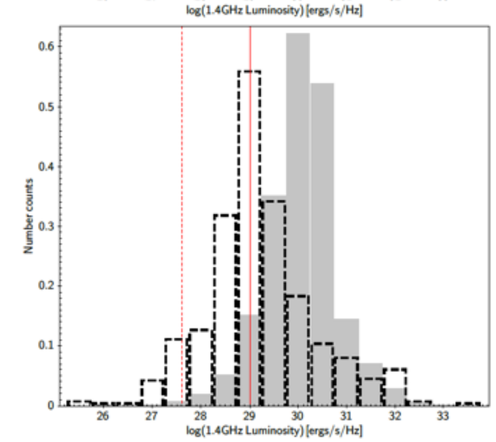
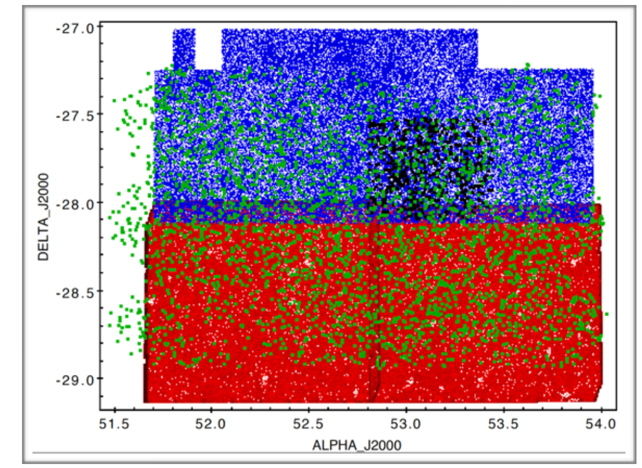








CDFS 1, 2
CDFS 3, 4
VLA
ATLAS DR3



Radio-loud

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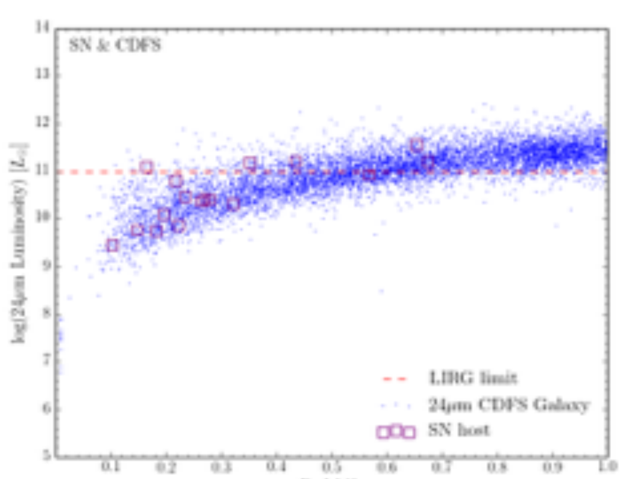

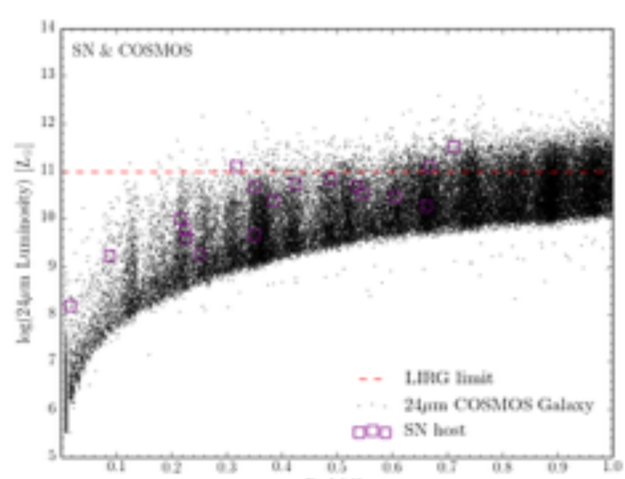

Graham+2010

0.1 < z < 0.6

Harutyunyan+ in preparation

SN rates as a function of galaxy radio & infrared power

Della Valle+2005

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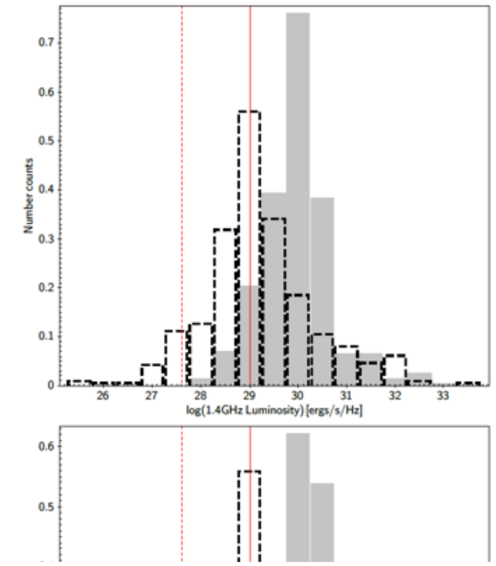

CDFS 1, 2
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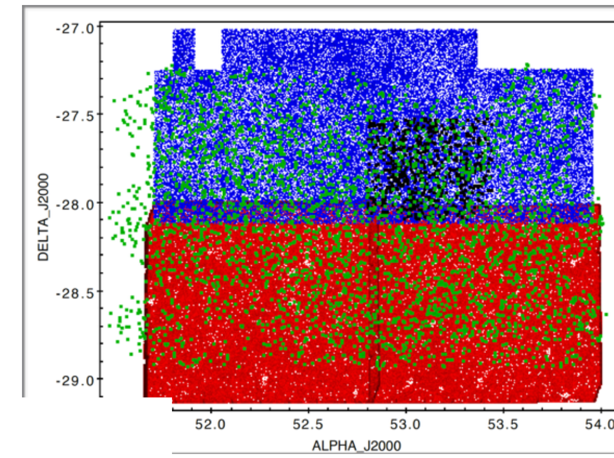

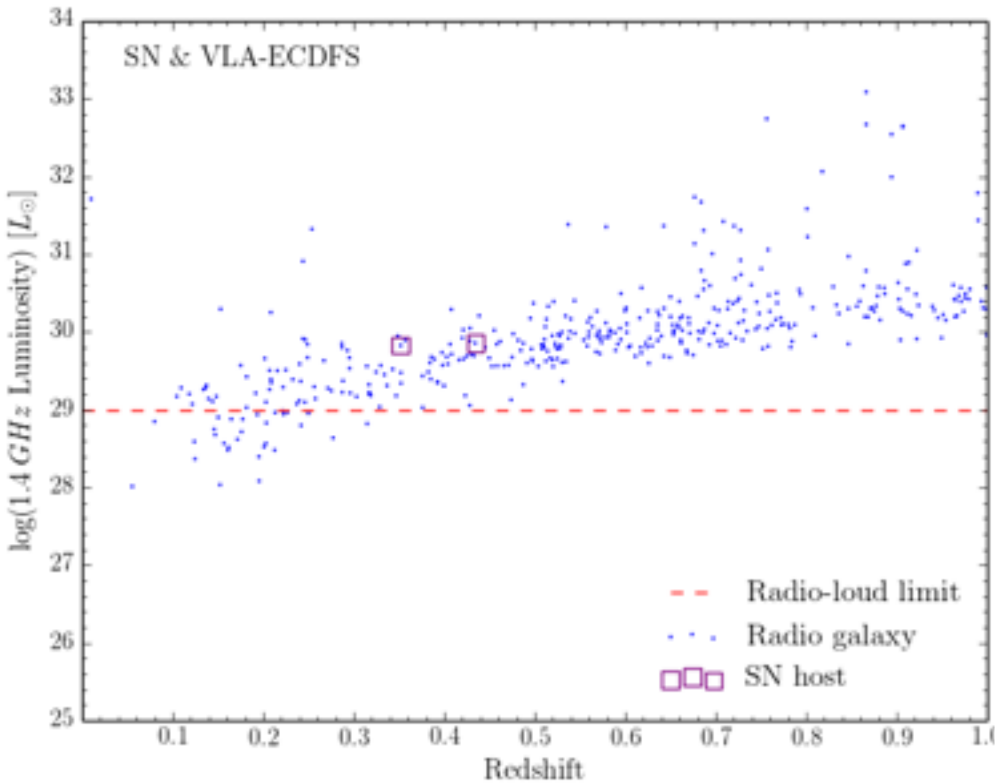

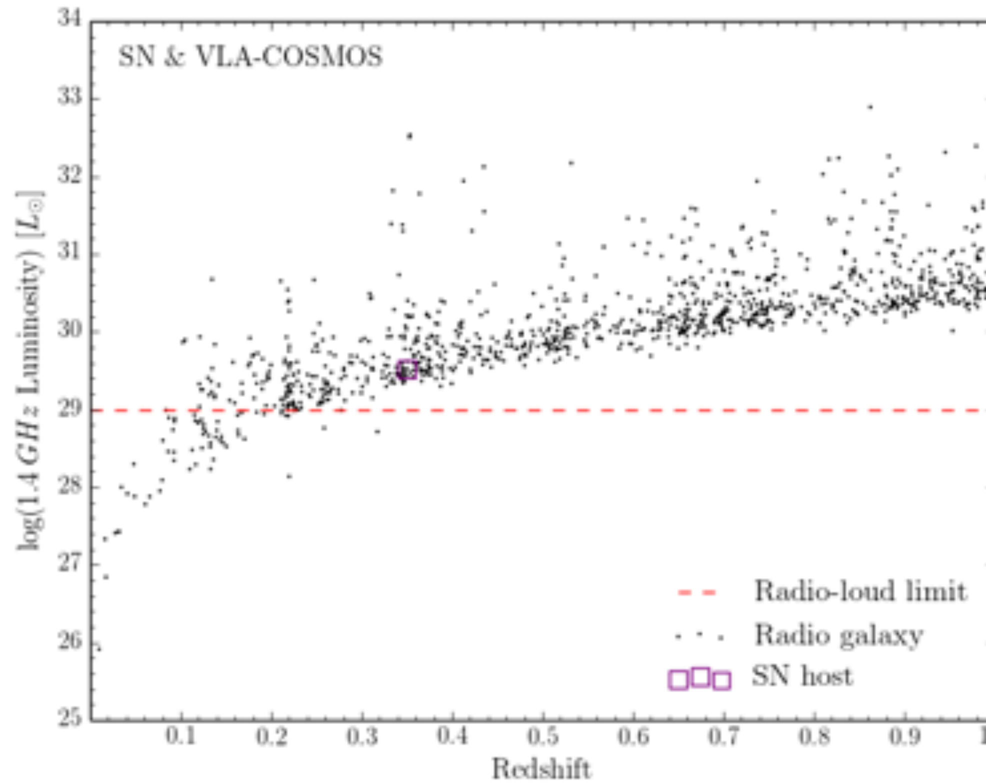

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-IRG-loud

MOS - Ia, II, IIn

- 2 Ia, 2 IIn, Ic

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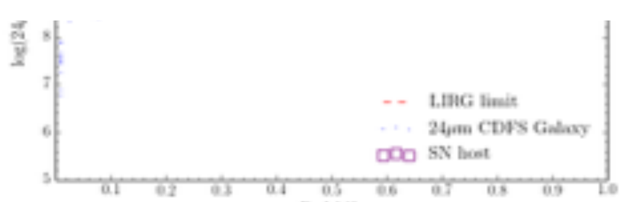

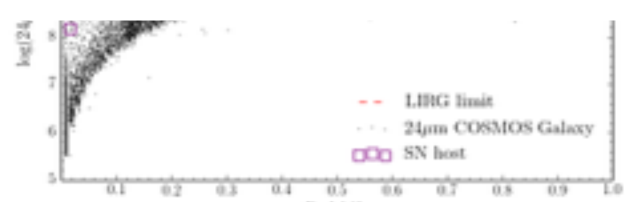

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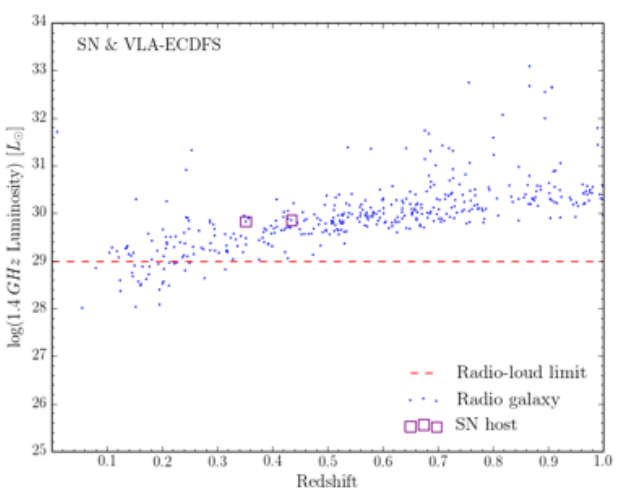

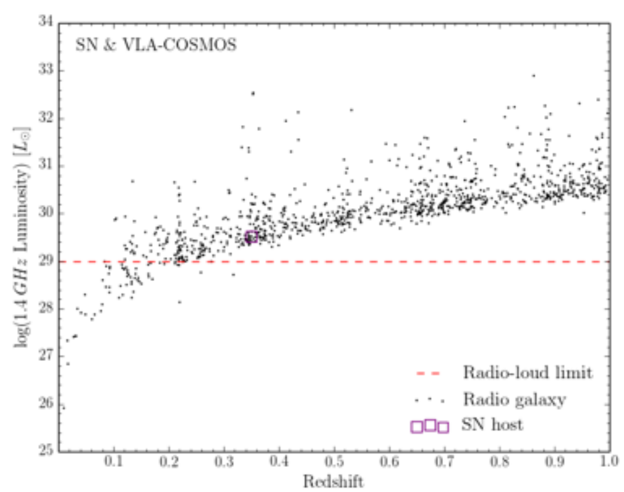

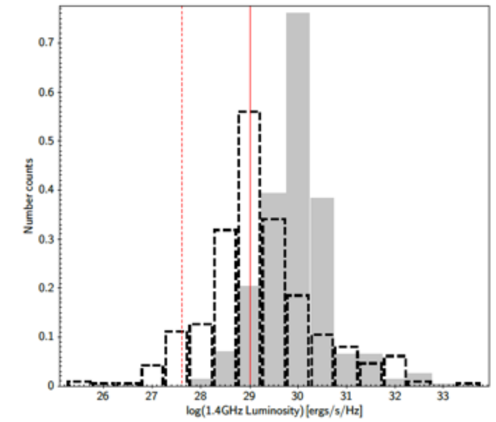

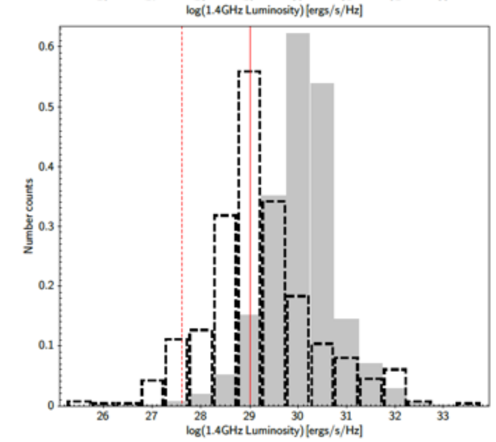

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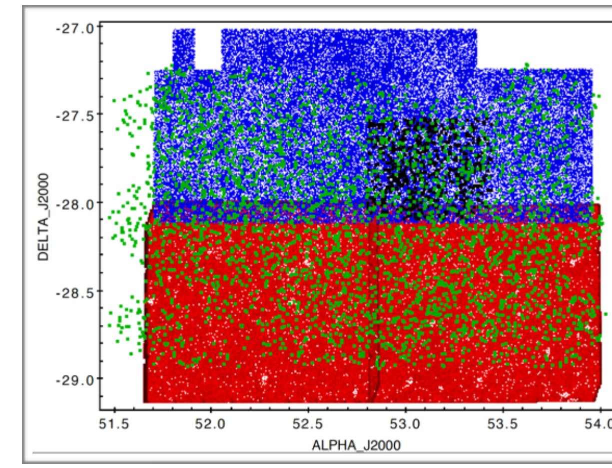
VLA
ATLAS DR3



Radio-loud

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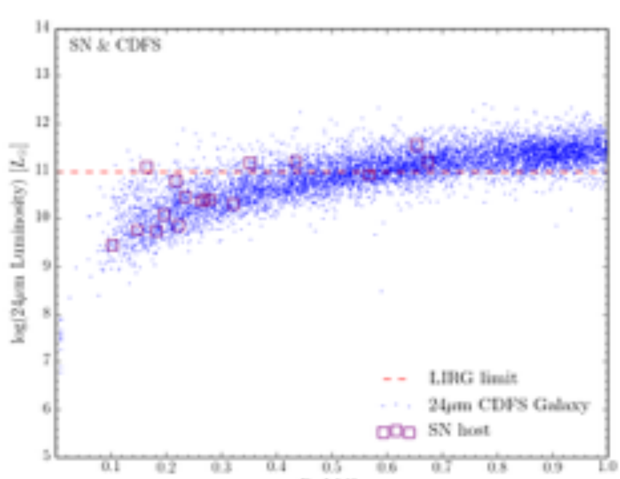

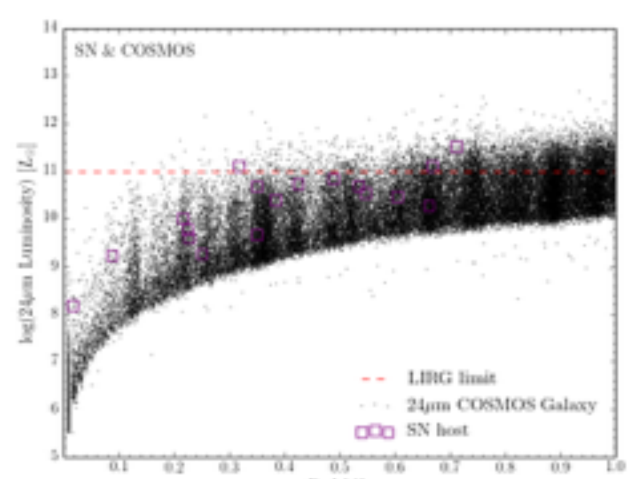

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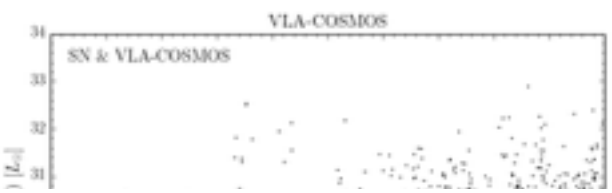
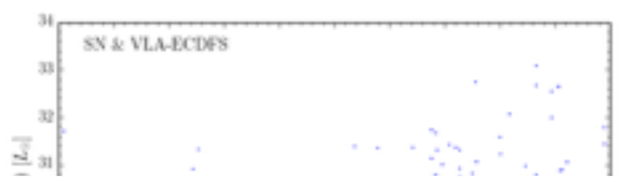
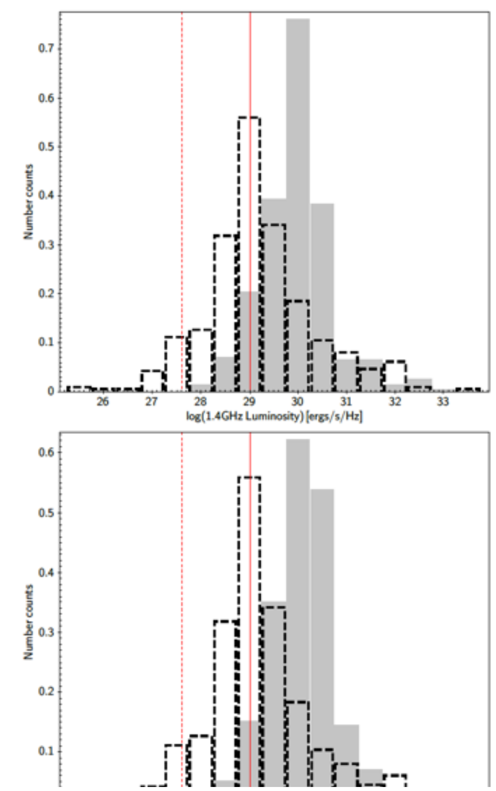




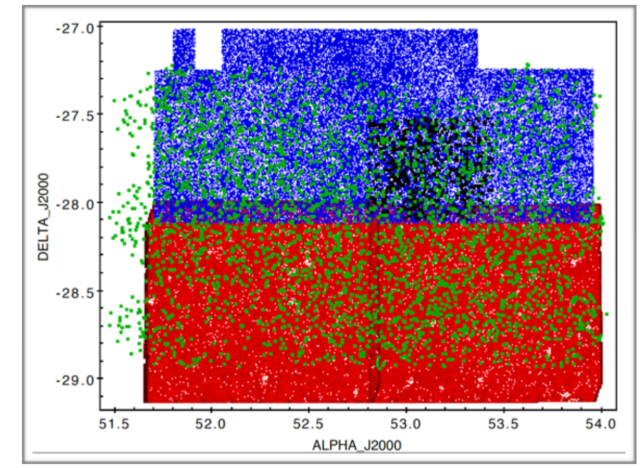


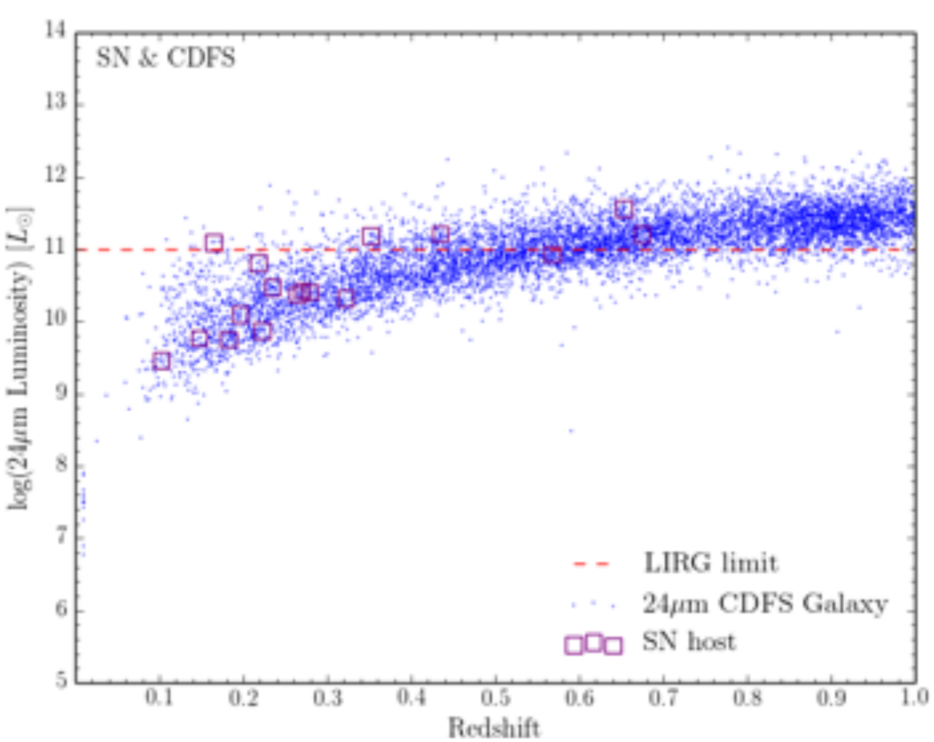
CDFS 1, 2

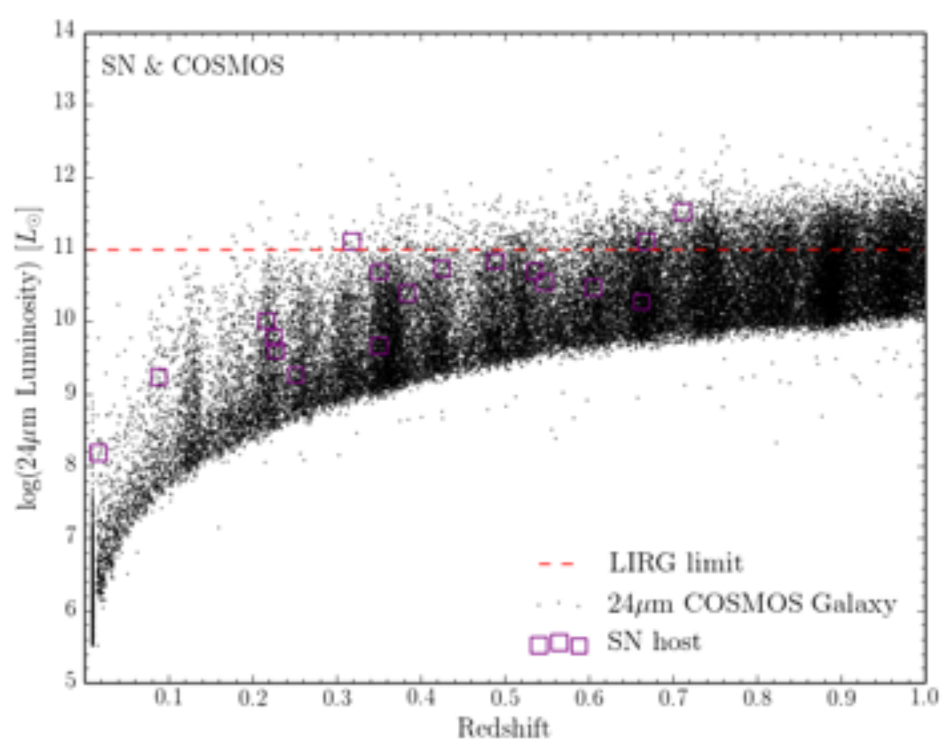
CDFS 3, 4

VLA

ATLAS DR3







COSMOS - Ia, II, IIn

CDFS - 2 Ia, 2 IIn, Ic

Graham+2010

$0.1 < z < 0.6$

Harutyunyan+ in preparation

Conclusions

- *rates per unit volume are in agreement with other results*
- *CC SN rates consistent with SFH assuming for 8-40 $M_\odot$ range*
- *the dispersion of SN Ia rate does not allow to discriminate between SD & DD models*
- *no evolution for type Ib/c, IIn consistent with local measurements, no SLSN gives the upper limit*
- *rates per unit mass as function of B-K colour have the same trend in local Universe and intermediate z*
- *both types CC & Ia SNe show more than an order of increase from passive to starburst galaxies*
- *clear increase of rates per unit mass with sSFR confirmed at intermediate z*