Obscured Star Formation in the Host Galaxies of Superluminous Supernovae

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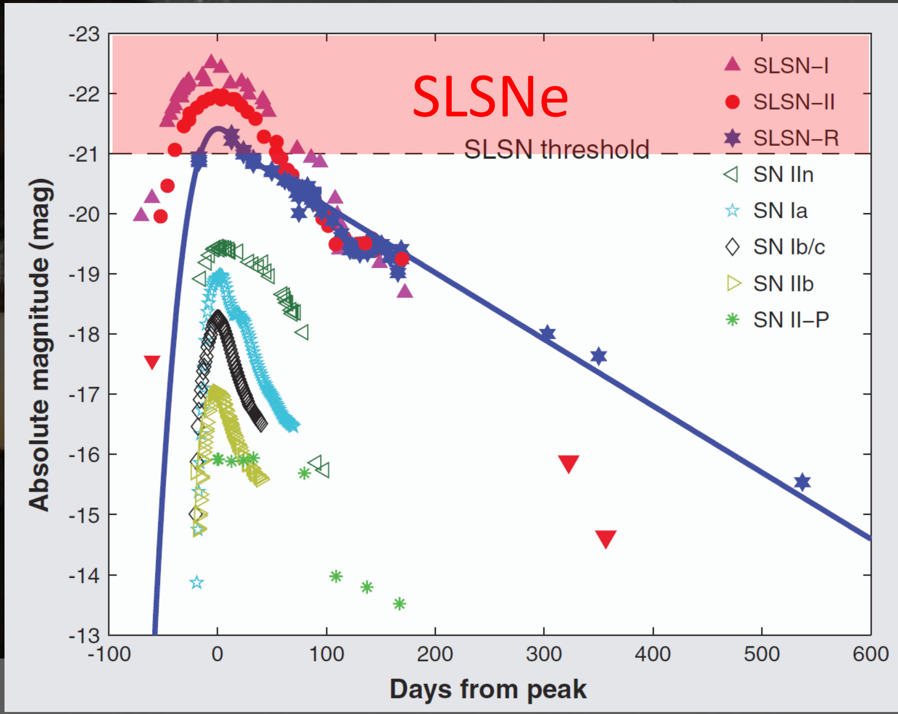
Superluminous Supernovae (SLSNe)

- Very bright explosions
  - peak absolute magnitudes of <~−21 mag
  - ~10-100 times brighter than ordinary Type Ia and core-collapse SNe
- a new class of SNe which were only discovered recently by wide-field time-domain surveys
- Detectable at high redshifts (z_{spec} = 3.9; Cooke+12)

→ Powerful indicators of environments in the distant universe



Light curves of SNe (Gal-Yam 12)

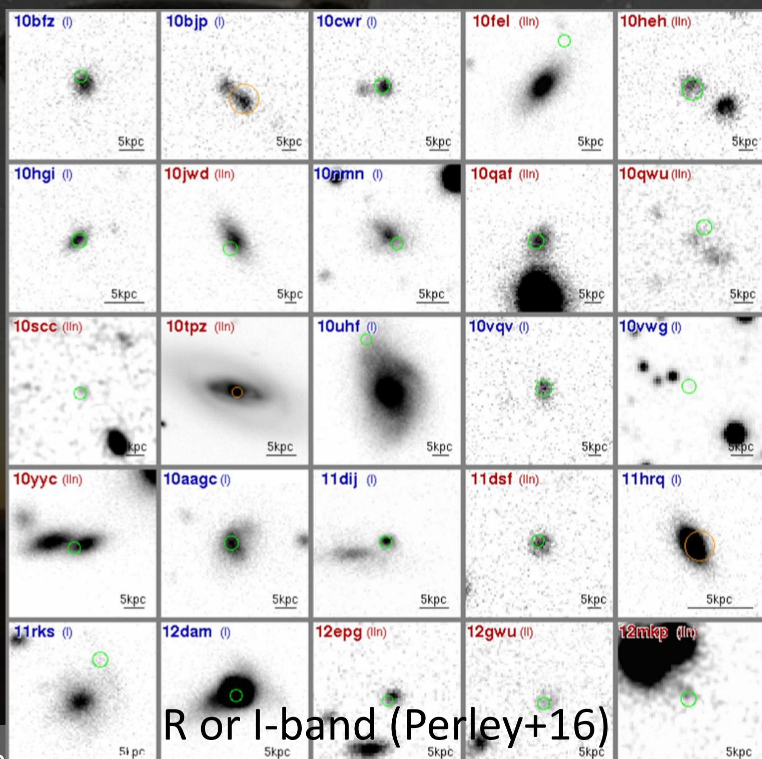
Physical Nature of Progenitor

- SLSN-II
  - hydrogen-rich in spectra
  - explained as an interaction with dense circumstellar medium
    - e.g., Woosley+07; Moriya+13
- SLSN-I
  - hydrogen-poor in spectra
  - physical nature of the progenitor is still a matter of debate
    - spin-down of a newborn strongly magnetic neutron star (magnetar; e.g., Kasen & Bildsten 10; Woosley 10)
    - fallback accretion onto a compact remnant (e.g., Dexter & Kasen 13)
    - pair instability SN (e.g., Gal-Yam+09)
    - SN which produces a large amount of 56Ni (e.g., Moriya+10)

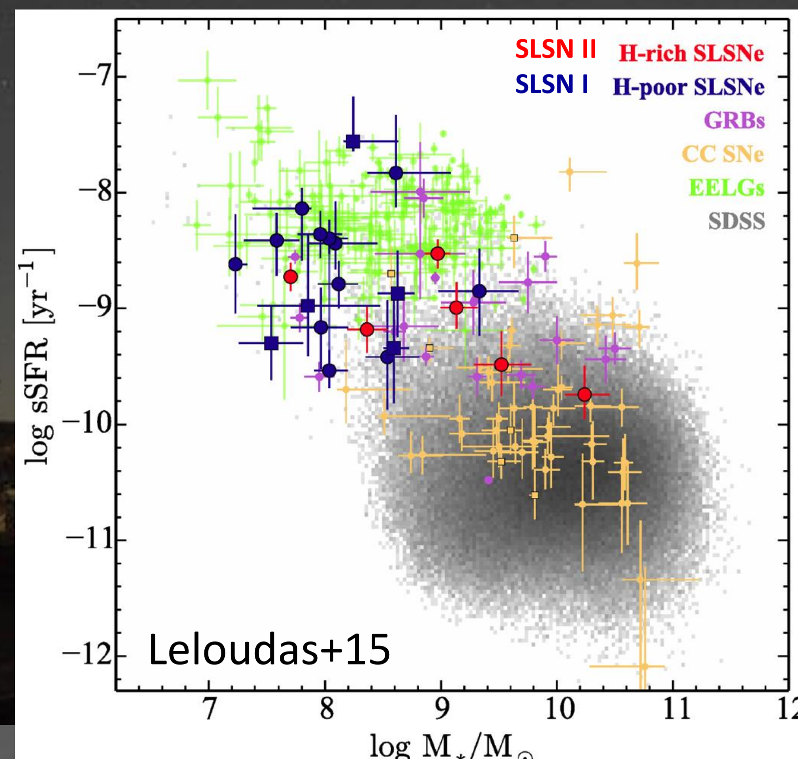
Host Galaxies

- SLSN-I hosts
  - dwarf galaxies (low luminosity, low stellar, low SFR) compared to local SF galaxies and the hosts of core-collapse SNe
- SLSN-II hosts
  - show a wider range

(e.g., Chen+13, 15, 17; Lunnan+14; Leloudas+15; Angus+16; Perley+16)



R or I-band (Perley+16)



Leloudas+15

SFRs in SLSN Hosts

- Previous studies
  - made exclusively in optical, which are subject to dust extinction in contrast to longer wavelengths

  ➔ it is possible that we are missing obscured star formation

- Radio observations
  - probe dust-obscured star formation
  - Schulze+18
    - searched radio emission from the survey data of FIRST, NVSS, SUMSS
      ➔ No host is detected with rms ~0.15, ~0.45, ~1.3 mJy/beam
    - deeper VLA observations of 3 hosts at z=0.1-0.3 ➔ non detection

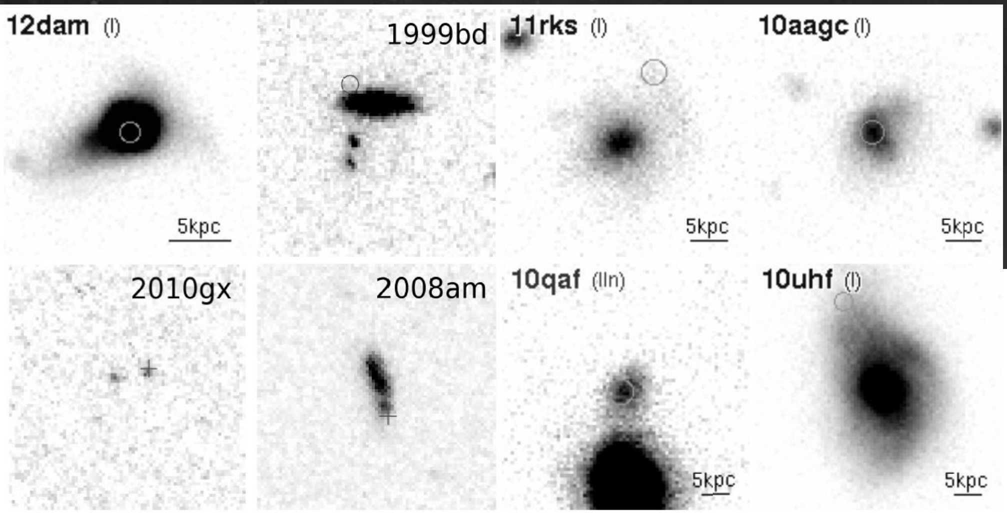
The number of hosts with deep radio observations is still very limited, and it is essential to study a larger sample

VLA Observations

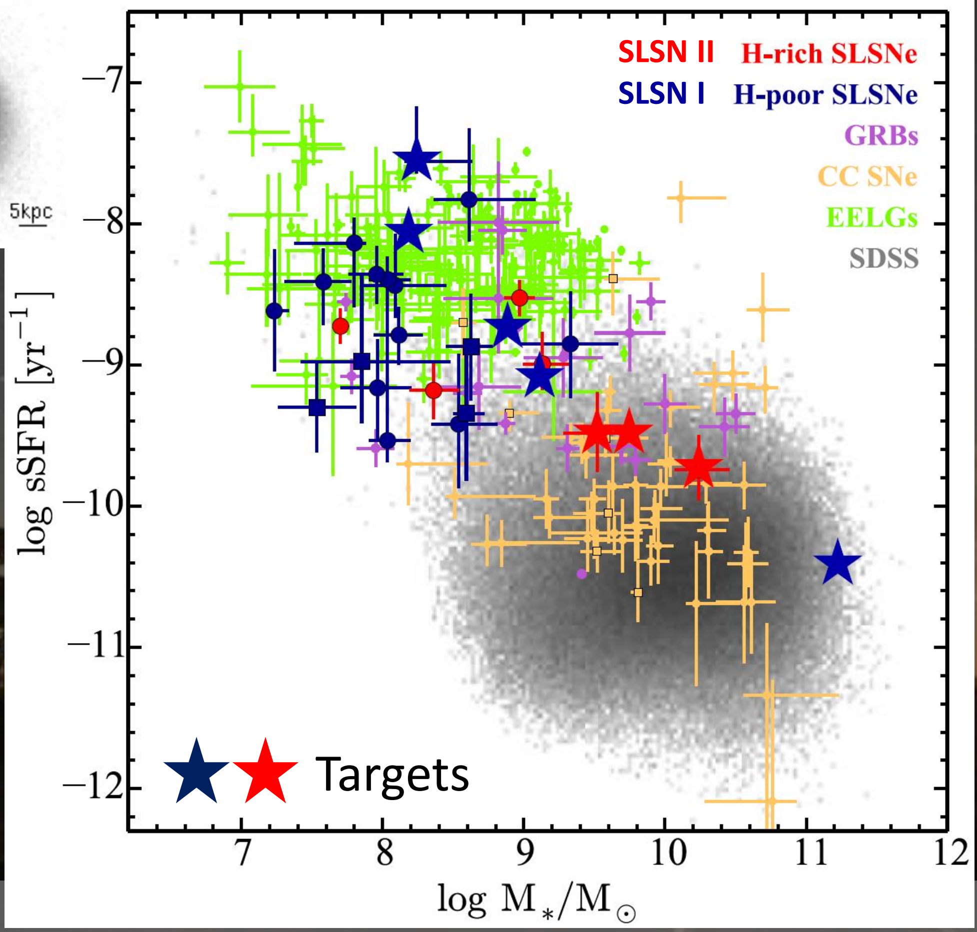
- Targets: 8 hosts
  - from comprehensive studies of SLSN hosts in the literature, where SFR, stellar mass, and other information are available
  - SFR(UV/opt) >~ 1 Msun/yr & z < 0.3, to ensure a significant constraint on obscured SF
  - excluding hosts that are known to have possible AGN features
    - Lunnan+14; Leloudas+15; Angus+16; Perley+16
- Observations on 2017 May 28-29
  - S band (3 GHz, 13 cm), C array configuration
  - on-source ~ 1.5 hr/source

SLSN	Class	z	R.A.[a] (J2000)	Decl.[a] (J2000)	SFR(SED)[b] ($M_\odot$ yr^{-1})	SFR(Hα)[c] ($M_\odot$ yr^{-1})	log(M_*)[d] ($M_\odot$)	12 + log(O/H)[e]
PTF 12dam	I-R	0.107	14:24:46.20	+46:13:48.3	$11.13^{+3.376}_{-3.339}$	$4.781^{+0.965}_{-1.174}$	$8.30^{+0.15}_{-0.15}$	$8.00^{+0.01}_{-0.01}$
SN 1999bd	II	0.151	09:30:29.17	+16:26:07.8	⋯	1.09 ± 0.34	$9.52^{+0.26}_{-0.24}$	8.52 ± 0.02
PTF 11rks	I	0.192	01:39:45.53	+29:55:27.4	$1.064^{+0.346}_{-0.429}$	$0.389^{+0.202}_{-0.147}$	$9.11^{+0.13}_{-0.16}$	$8.17^{+0.11}_{-0.17}$
PTF 10aagc	I	0.206	09:39:56.92	+21:43:17.1	$1.566^{+1.049}_{-0.646}$	$0.474^{+0.187}_{-0.160}$	$8.98^{+0.13}_{-0.21}$	$8.19^{+0.04}_{-0.05}$
SN 2010gx	I	0.230	11:25:46.71	−08:49:41.4	$0.532^{+0.287}_{-0.248}$	$0.257^{+0.052}_{-0.051}$	$7.87^{+0.13}_{-0.21}$	$7.94^{+0.09}_{-0.14}$
SN 2008am	II	0.234	12:28:36.30	+15:34:50.0	⋯	1.38 ± 0.39	$9.13^{+0.19}_{-0.14}$	8.35 ± 0.02
PTF 10qaf	II	0.284	23:35:42.89	+10:46:32.9	⋯	3.13 ± 0.89	$10.24^{+0.22}_{-0.17}$	8.68 ± 0.04
PTF 10uhf	I	0.288	16:52:46.70	+47:36:21.8	$6.837^{+2.227}_{-3.103}$	$19.36^{+7.301}_{-5.764}$	$11.23^{+0.12}_{-0.15}$	$8.70^{+0.01}_{-0.01}$

Targets

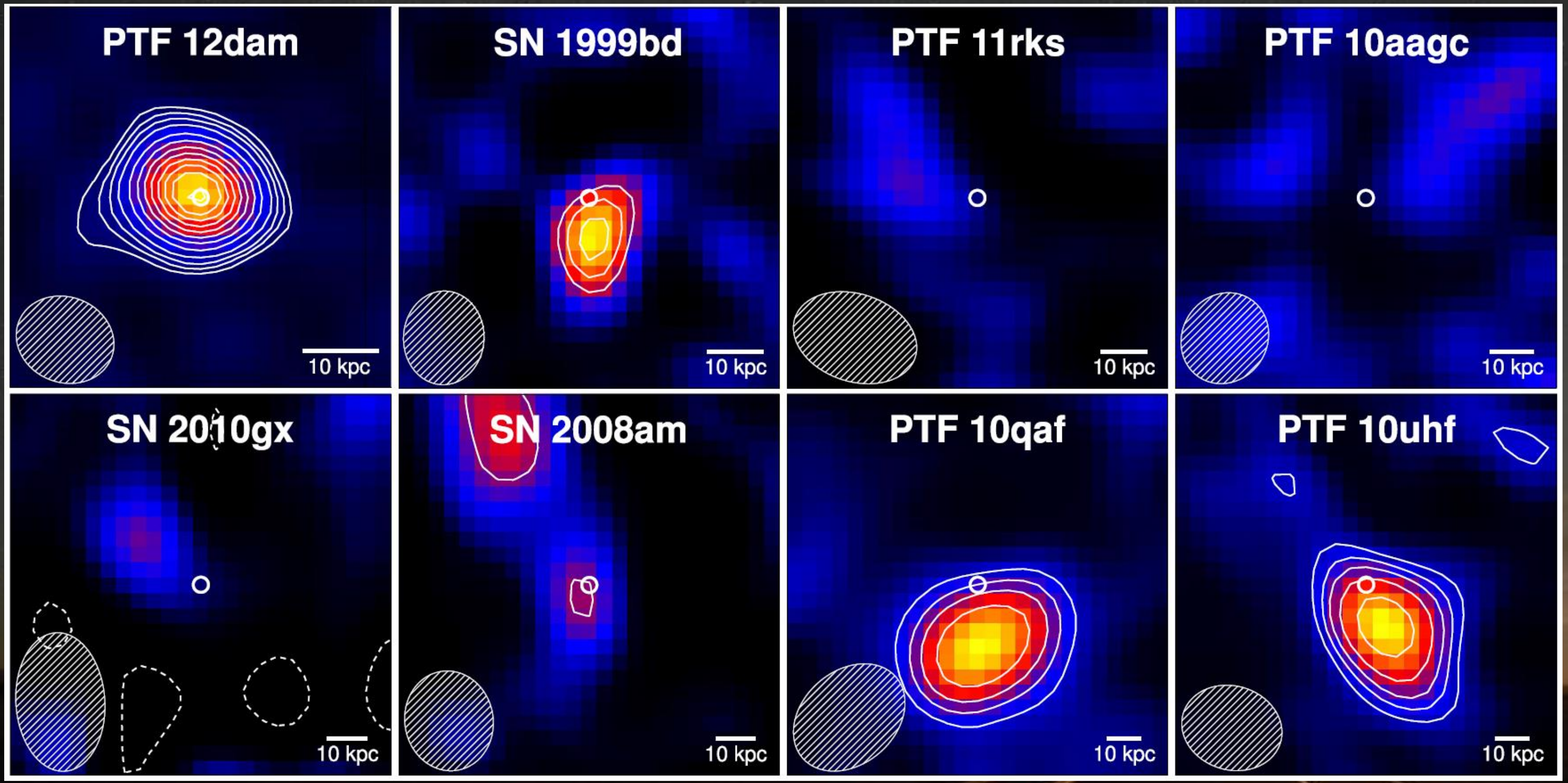


NIR images (10” x 10” : Angus+16; Perley+16)
Circles and crosses: SLSN positions



Results

- 4 detection, 1 tentative, and 3 non detection



25” x 25”. Contours -2.5σ, 2.5σ, 3.5σ, 4.5σ, and 2.5σ steps subsequently

SFR

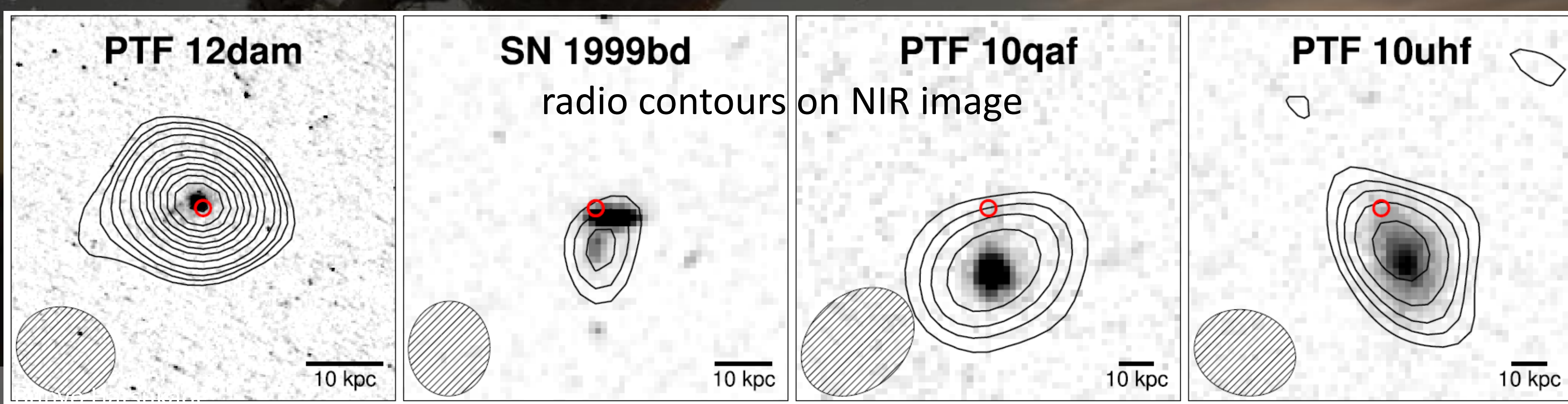
- Radio-derived SFR

$$\left(\frac{SFR_{\mathrm{Radio}}}{M_{\odot}/\mathrm{yr}}\right) = 0.059\left(\frac{F_{\nu}}{\mu\mathrm{Jy}}\right)(1+z)^{-(\alpha+1)}\left(\frac{D_{\mathrm{L}}}{\mathrm{Gpc}}\right)^{2}\left(\frac{\nu}{\mathrm{GHz}}\right)^{-\alpha}$$

(Murphy+11)

  - assume α = -0.75 (spectral slope of radio continuum)

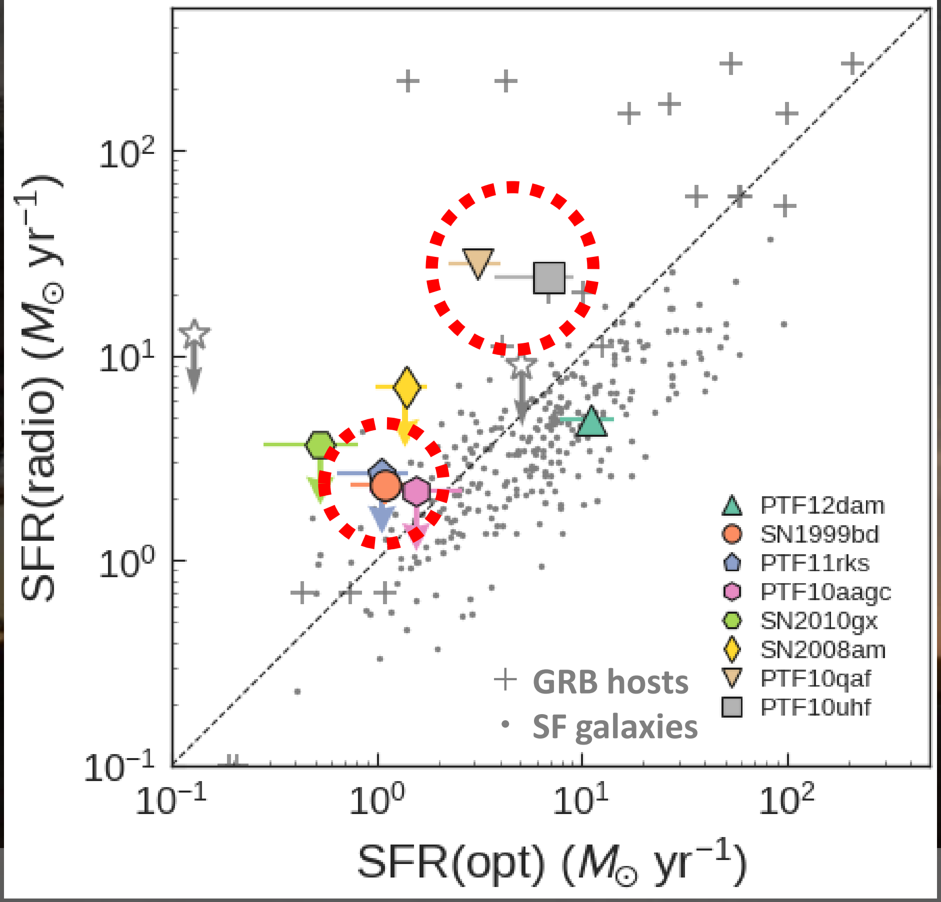
- The hosts of PTF 10qaf and PTF 10uhf have high SFRs (>20 Msun/yr), making them the most intensely star-forming galaxies among SLSN hosts



Obscured Star Formation

- SFR(radio) is larger than SFR(opt) in 3 hosts
  - SN 1999bd, PTF 10qaf, PTF 10uhf
  - by a factor of 2-9

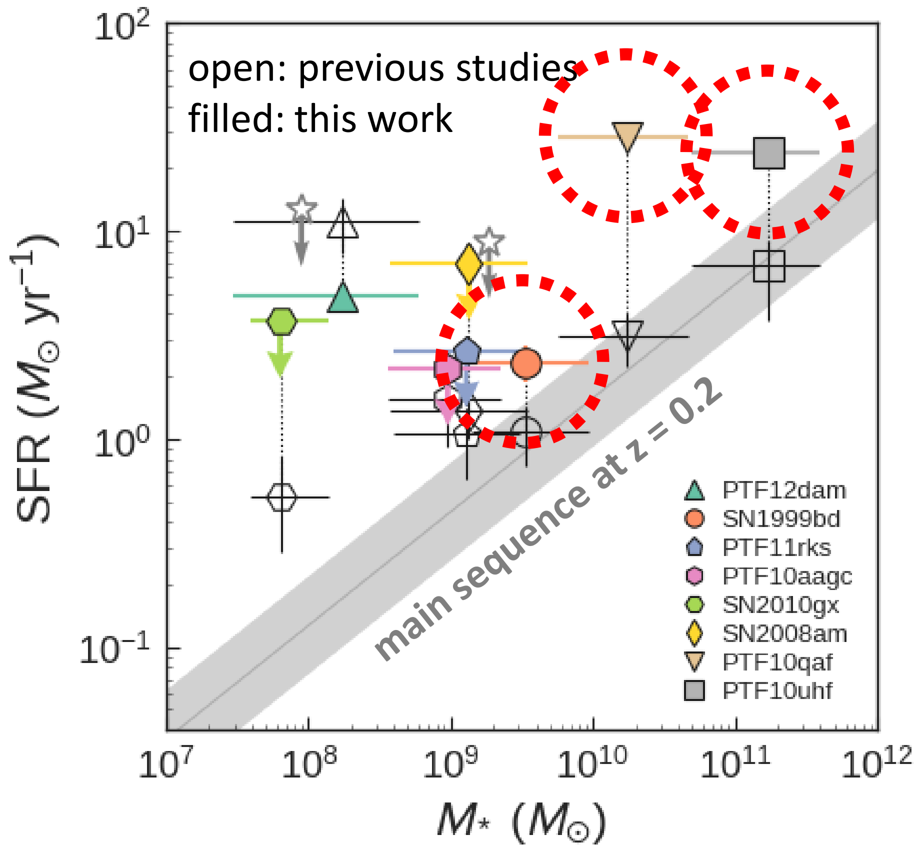
→ **Obscured SF**



Stellar Mass and SFRs

- Previous studies: SN 1999bd, PTF 10qaf, and PTF 10uhf are on the main-sequence of SF galaxies
- Radio: they are above the sequence ➔ starburst nature

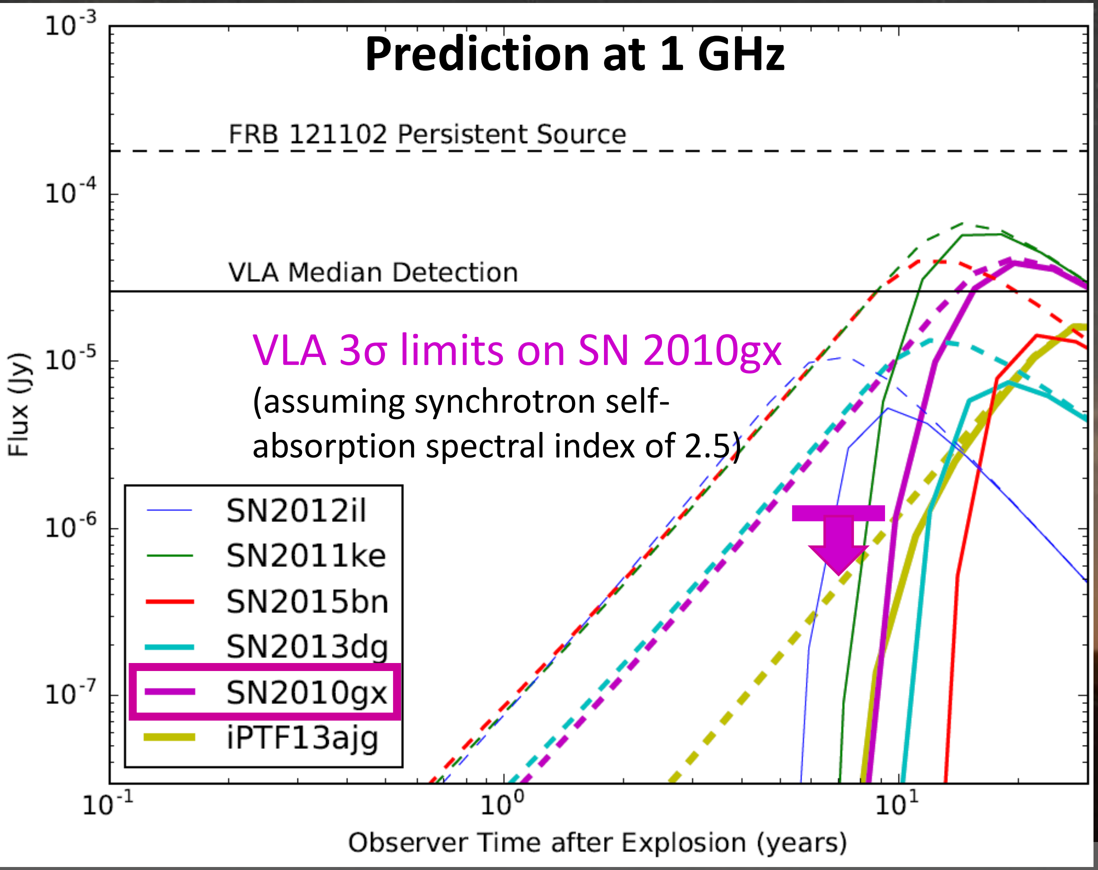
➔ a higher fraction of starbursts in SLSN hosts than estimated



c.f., ≈5% of local SF galaxies; Perley+16

Constraint on Pulsar-driven SN Model

- Pulsar-driven SN remnants cause quasi-steady synchrotron emission associated with nascent pulsar wind nebulae (PWNe)
  - Murase+16; Kashiyama & Murase 17; Omand+18
- Radio emission increases with time, reaches its peak at ~10-30 yr



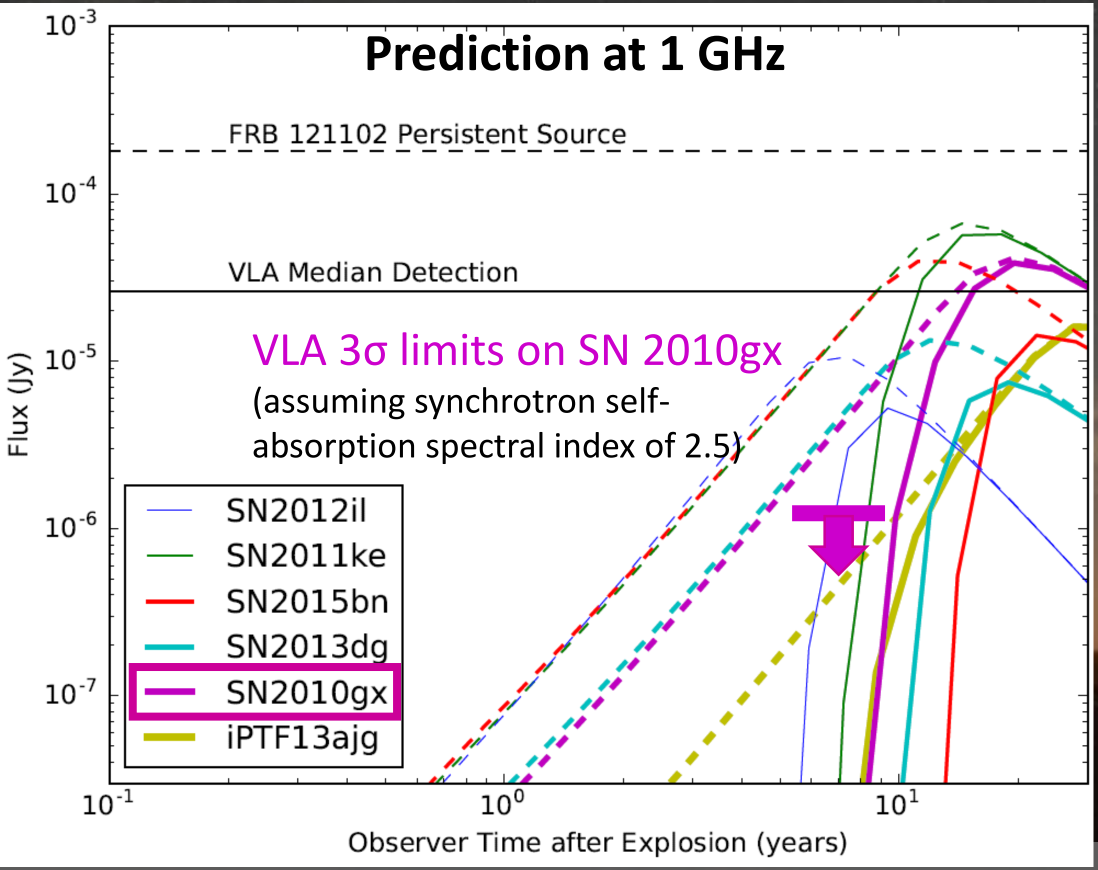
dashed lines: no absorption in PWN and SN ejecta

solid lines: include absorption processes

Omand+18

Constraint on Pulsar-driven SN Model

- The predicted radio emission of SN 2010gx for the case of no absorption processes is inconsistent with our 3σ upper limit



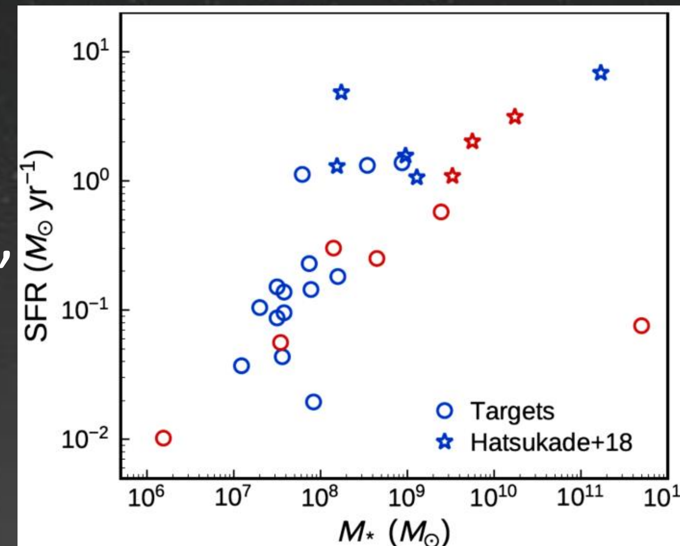
dashed lines: no absorption in PWN and SN ejecta

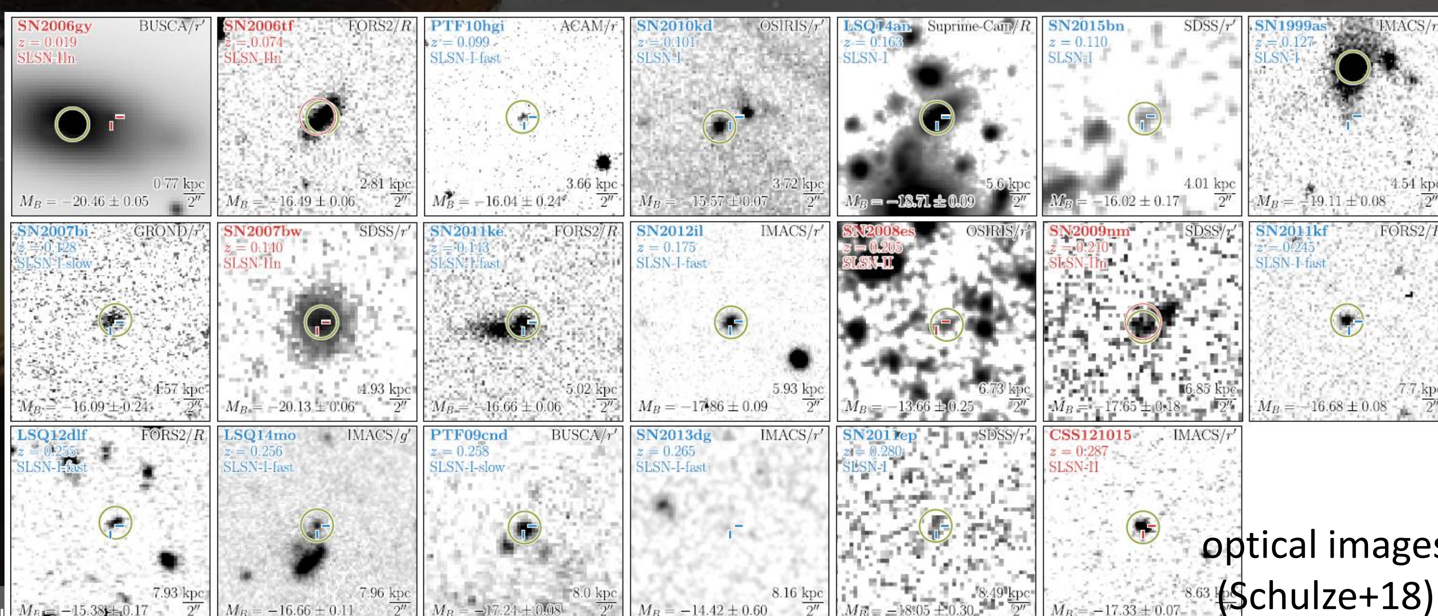
solid lines: include absorption processes

Omand+18

Future Work 1

- Current sample is dominated by higher-SFR and stellar mass hosts
- To understand the general properties, a volume-limited sample of 20 SLSN hosts at z < 0.3 is observed with VLA
- 24 hr at Priority C (filler)



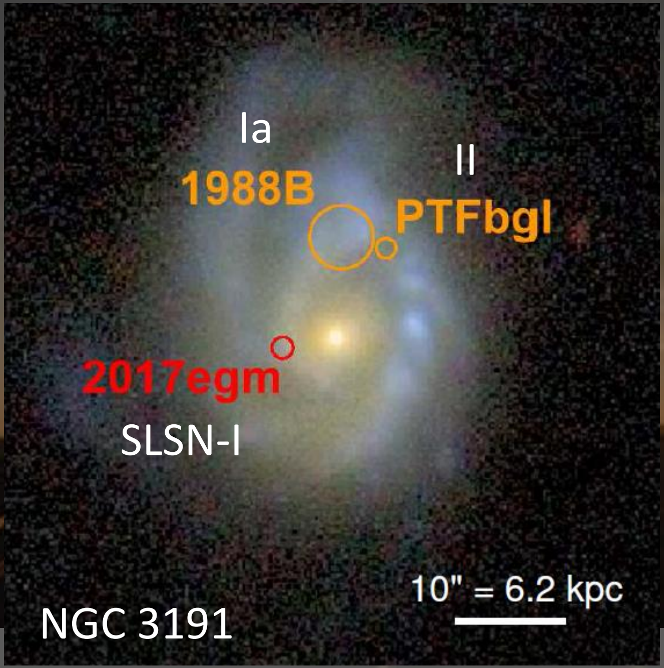


optical images (Schulze+18)

Future Work 2

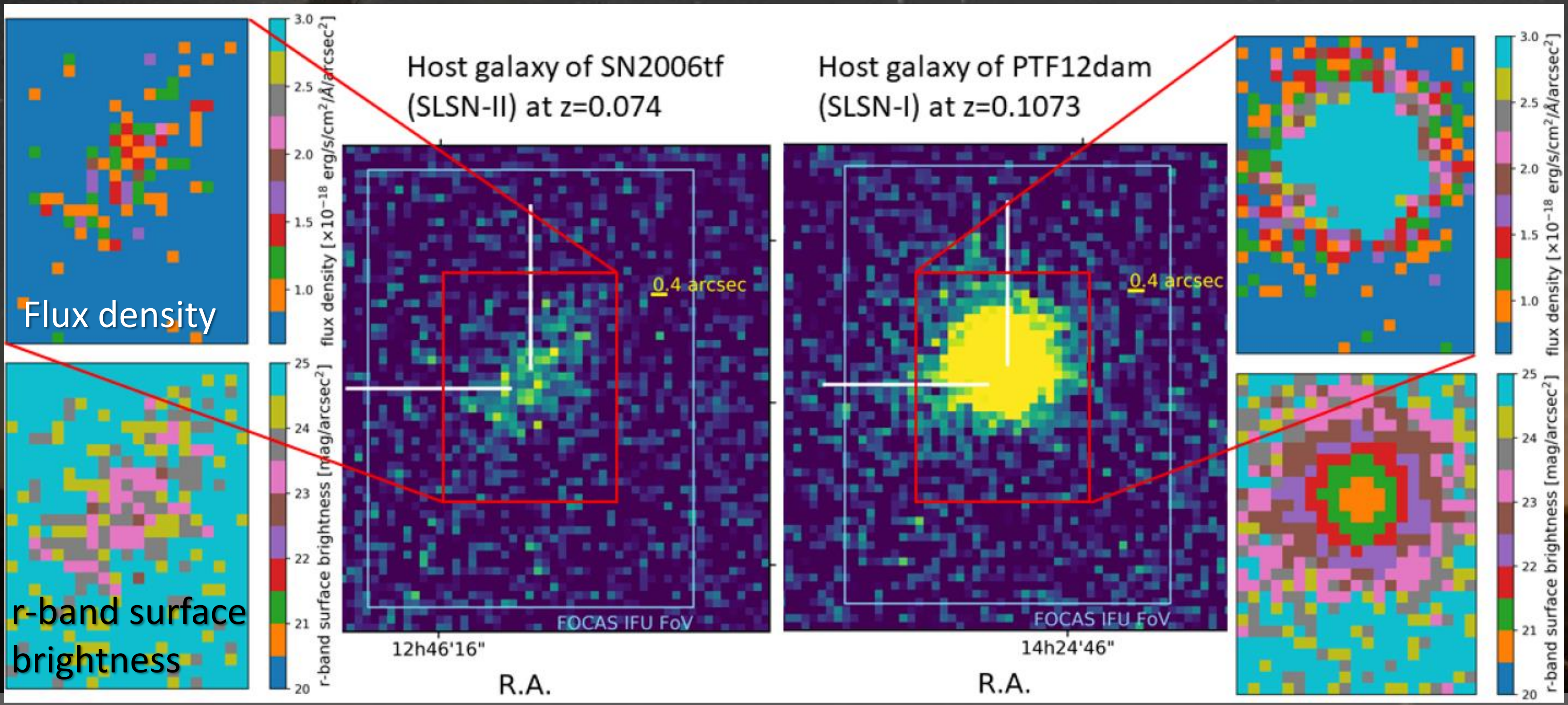
- ALMA study of SLSN2017egm host (B-rank, cycle 6)
  - SLSN-I
  - z = 0.03063, one of the closest SLSNe
  - spatially-resolving (500 pc) multiple CO line observations
  - investigate properties characteristic of SLSN environment
  - M* ~ (2-5)x10^{10} Msun, SFR ~ 15 Msun/yr

- Observations
  - CO(1-0)@Band6 & CO(3-2)@Band 7
  - dust continuum at band 7
  - beam size 0.8" (~500 pc)
  - 12m + ACA



Future Work 3

- Subaru/FOCUS IFU proposal (19A)
  - SN2006tf (z = 0.074), PTF12dam (z = 0.1073)
  - spatially-resolved stellar population age, star formation, metallicity, and ionization parameter



Summary

- VLA 3 GHz observations of 8 SLSN hosts (0.1 < z < 0.3)
  - 4 hosts are significantly detected
- Two hosts have high SFRs (>20 Msun/yr)
  → most intensely star-forming galaxies among SLSN hosts
- Three hosts have an excess of SFR(radio) over SFRs(opt) by >2
  → obscured star formation
- They are above the main sequence
  → a higher fraction of starbursts in SLSN hosts
- Observations place a constraint on a pulsar-driven SN model
- Future Works
  - increase the sample size (>20 hosts)
  - spatially-resolved molecular gas, dust-obscured SF, stellar population