Radio and Submillimetre Constraints on the Pulsar-Driven Supernova Model

Conor Omand
+ Many Collaborators

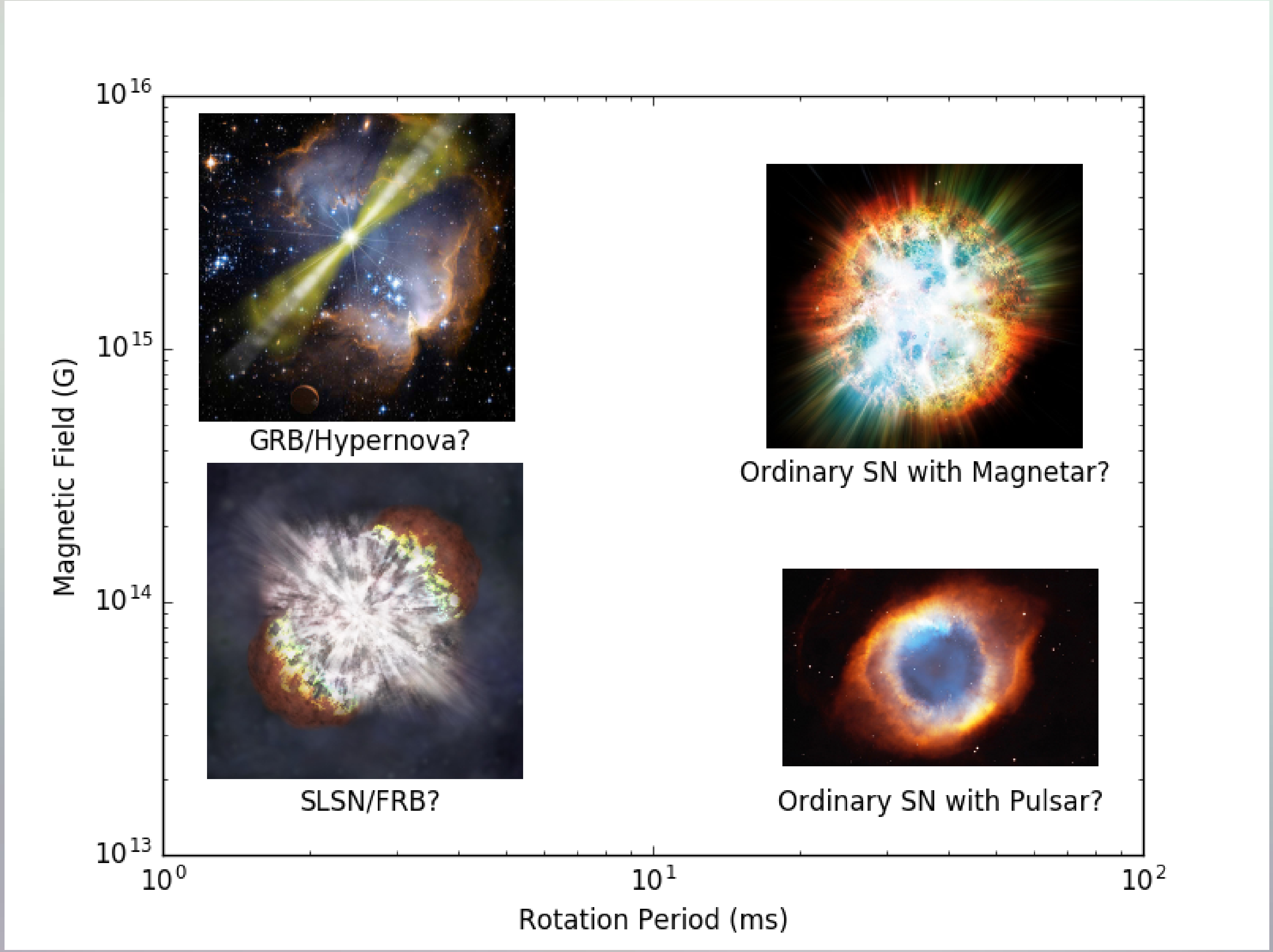
Based on:
Omand, Kashiyama, Murase (2018)
Law, Omand et al. (2019)
Murase, Omand et al. (in prep)
Omand, Kashiyama, Murase (preliminary)

VLA/NRAO/AUI/NSF; Chandra/CXC; Spitzer/JPL-Caltech; XMM-Newton/ESA; and Hubble/STScI. https://commons.wikimedia.org/w/index.php?curid=5880957)

What is the Pulsar-Driven Supernova Model?

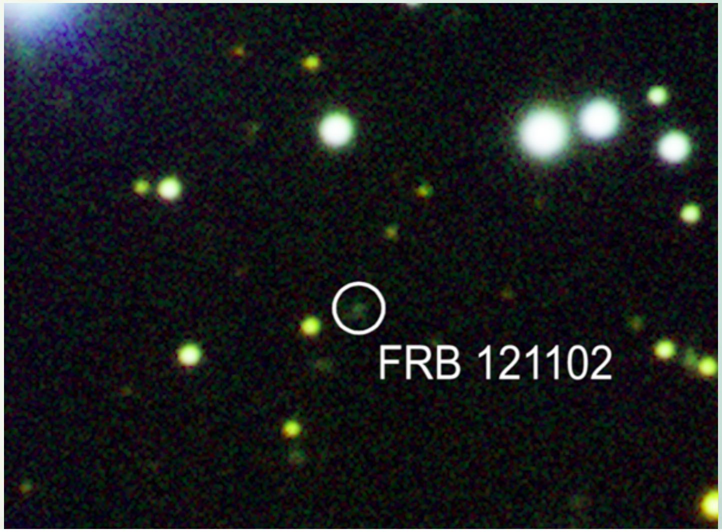
- The discovery of SLSNe and GRBs necessitates an energy source
- A newly formed highly magnetic millisecond pulsar spins down inside a young supernova, injecting energy into the ejecta
- In order to test the pulsar-driven SN model for Type I SLSNe, late-phase emission should be probed

A variety of Pulsar-Driven Transients

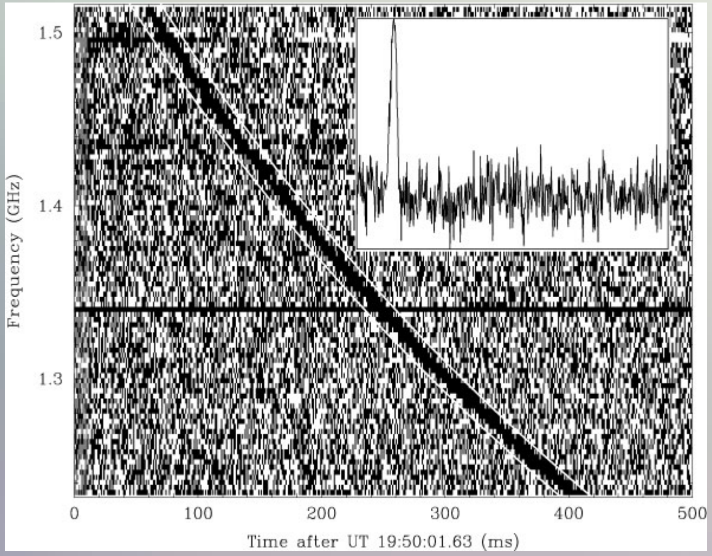


Fast Radio Bursts (FRBs)

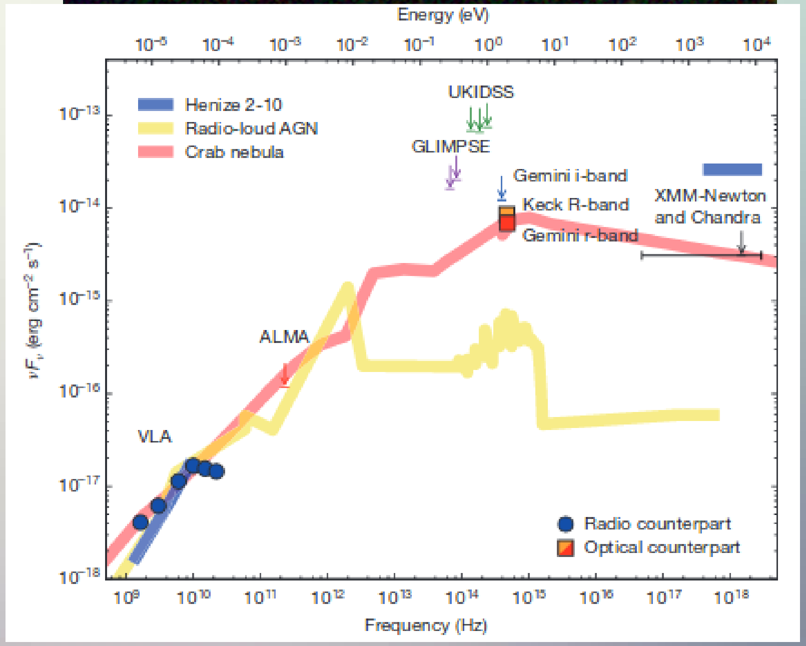
- One repeating source, FRB 121102 localized to z~0.2 dwarf, star-forming galaxy



Gemini Observatory/AURA /NRC/NSF/NRAO

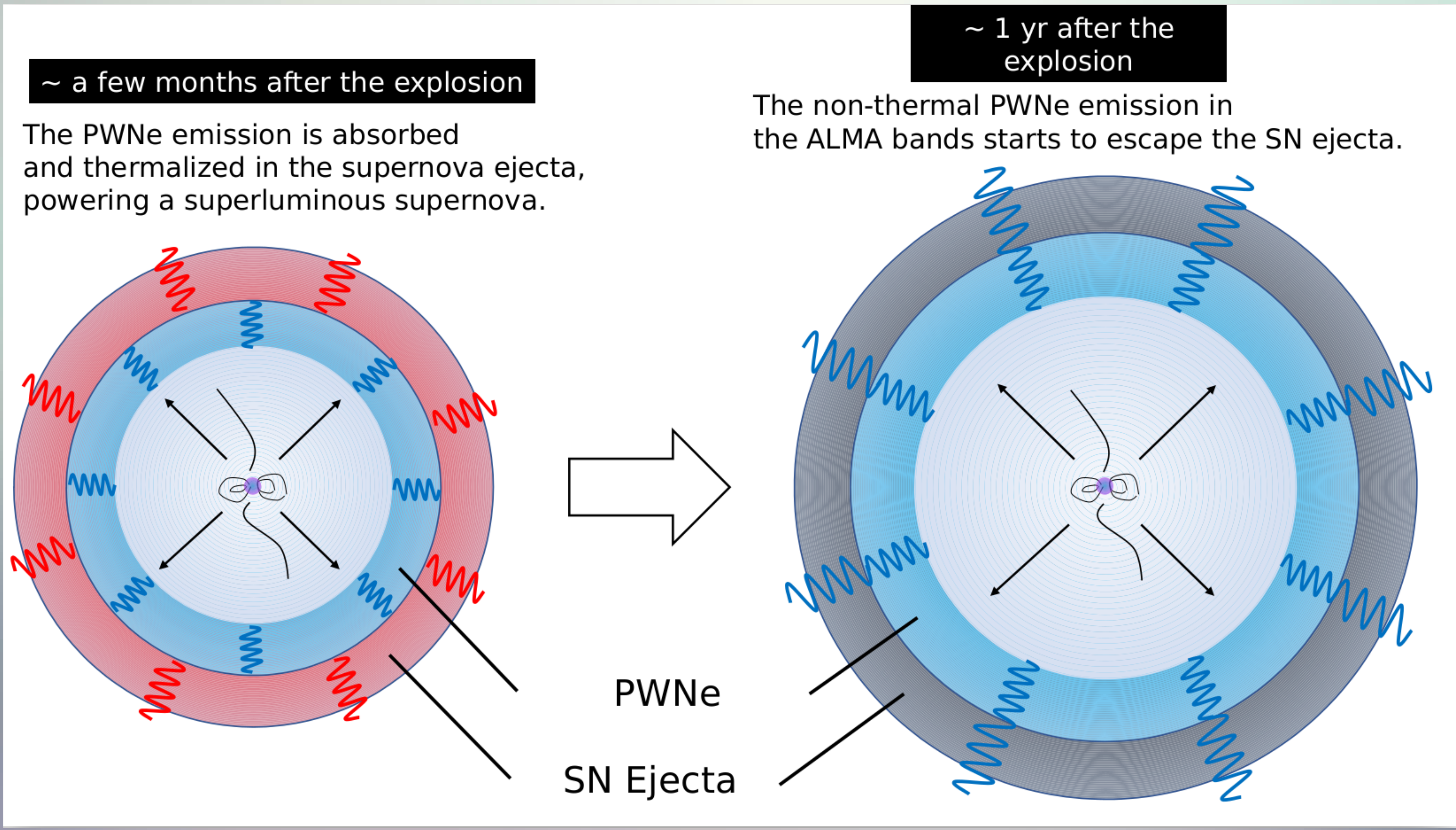


D. R. Lorimer et al., Science, 318, 777 (2007)



S. Chatterjee et al., Nature 541, 58–61 (2017)

Model Overview

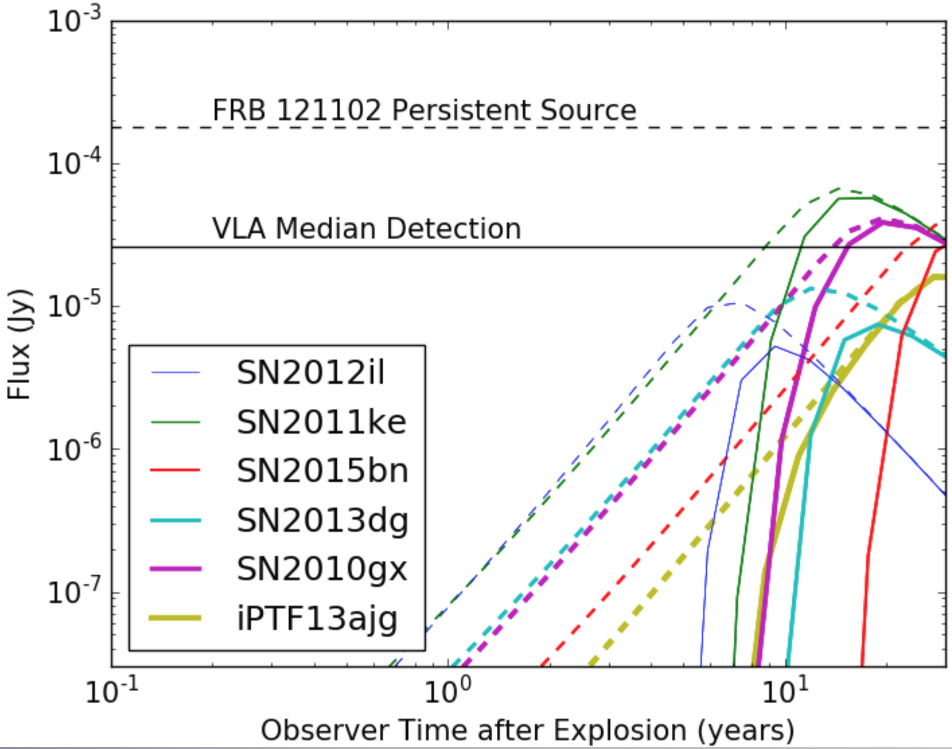


Strategy

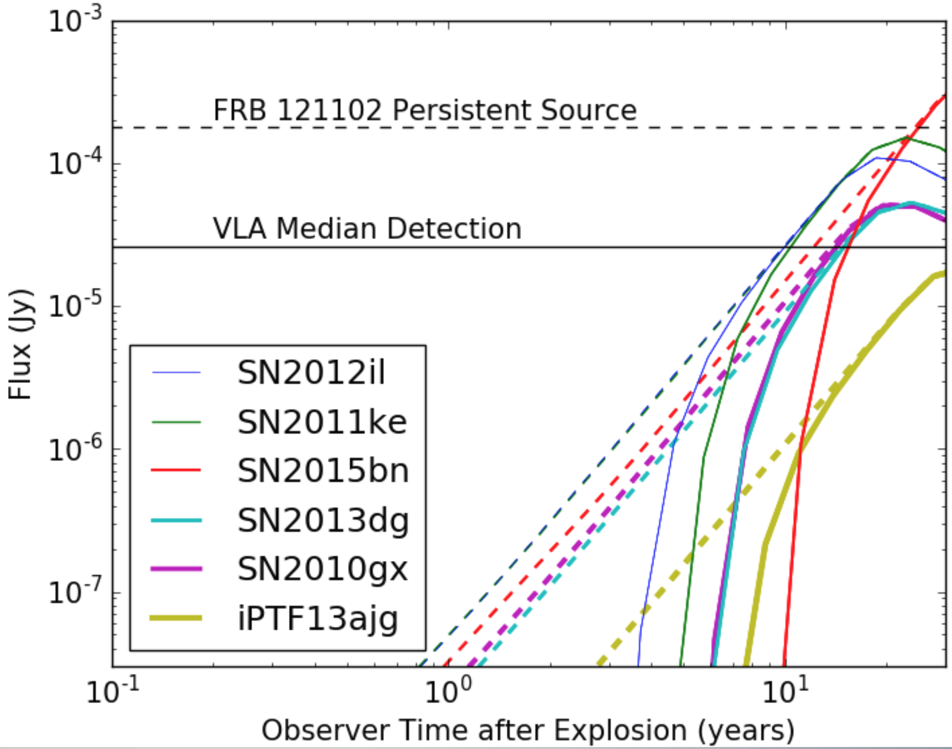
- Predict emission from young SLSN remnants in radio/submillimetre (Omand+ (2018))
- Observe oldest candidates in radio (Law, Omand+ (2019))
- Select promising candidates in submillimetre and observe (Murase, Omand+ (in prep))
- Revise the model if needed (Omand+ (prelim))

Predictions (1 GHz Radio emission)

P = 1 ms



P = P_{max}



Omand+ (2018)

VLA Targets

Table 1. SLSN-I Sample

Name	Redshift	R.A. (J2000)	Decl. (J2000)	Age (yr)
SN 2005ap[a]	0.283	13:01:14:83	+27:43:32:3	9.9
SN 2007bi	0.127	13:19:20:14	+08:55:43:7	9.4
SN 2006oz	0.396	22:08:53:56	+00:53:50:4	8.0
PTF10hgi[c]	0.098	16:37:47:04	+06:12:32:3	6.8
PTF09cnd	0.258	16:12:08:94	+51:29:16:1	6.6
SN 2010kd	0.101	12:08:00:89	+49:13:32:9	6.4
SN 2010gx[b]	0.23	11:25:46:71	-08:49:41:4	6.2
PTF09cwl	0.349	14:49:10:08	+29:25:11:4	6.1
SN 2011ke	0.143	13:50:57:77	+26:16:42:8	5.7
PTF09atu	0.501	16:30:24:55	+23:38:25:0	5.5

[a] Late-time radio limit at 1.4 GHz by Schulze et al. (2018).

[b] Late-time radio limit at 3 GHz by Hatsukade et al. (2018).

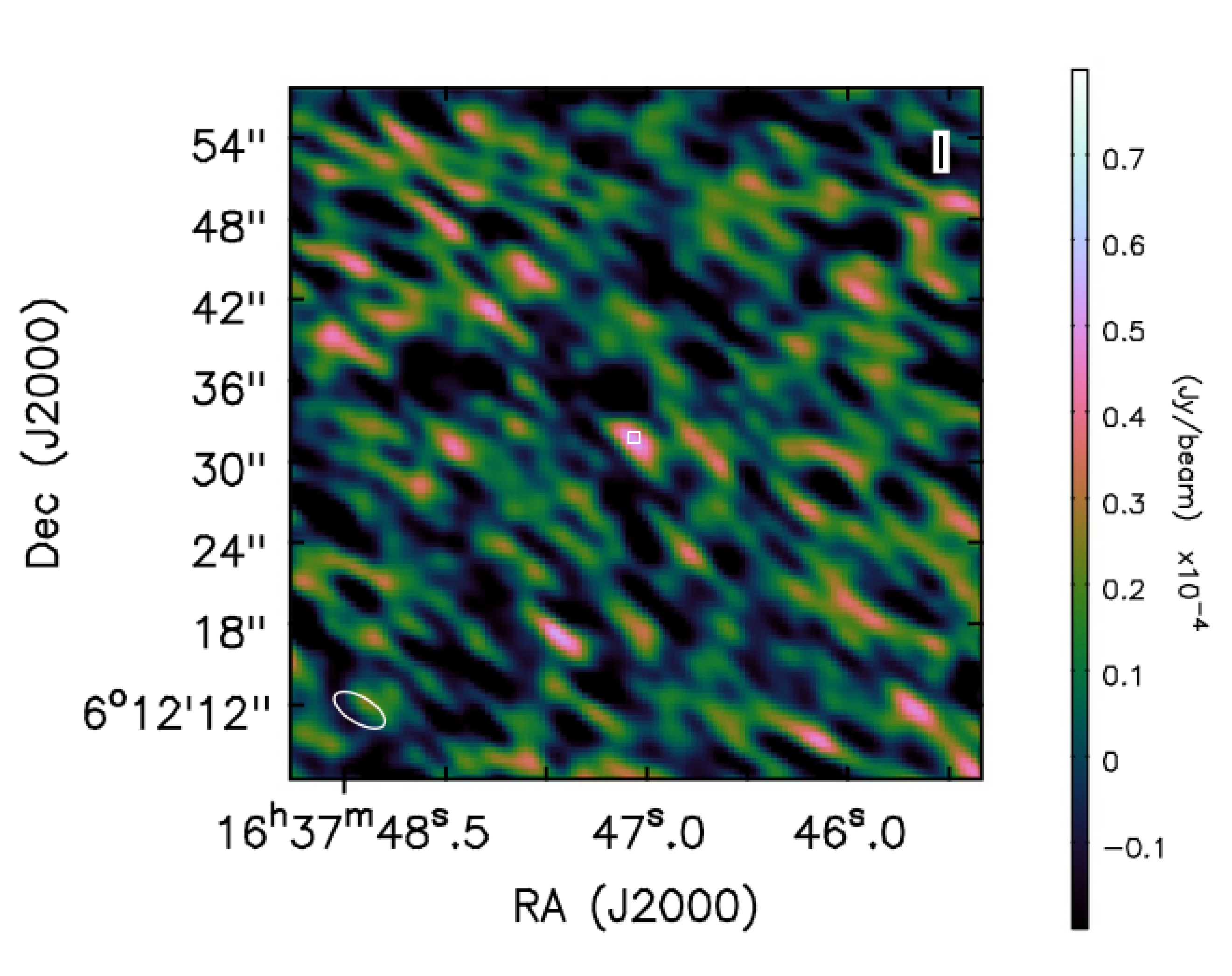
[c] Late-time radio detection at 6 GHz by Eftekhari et al. (2019).

Table 2. Observations of SLSN-I

Name	Epochs (MJD)	Obs. Time (min)	Sensitivity (μJy beam^{-1}; 1σ)
SN 2005ap	58060, 58131	57	10
SN 2007bi	58074, 58128	34	22
SN 2006oz	58036, 58124	60	8
PTF10hgi[a]	58045, 58130	26	14
PTF09cnd	58045, 58130	46	11
SN 2010kd	58074, 58128	27	14
SN 2010gx	58074, 58128	41	11
PTF09cwl	58060, 58131	73	9
SN 2011ke	58060, 58131	35	12
PTF09atu	58045, 58130	109	8

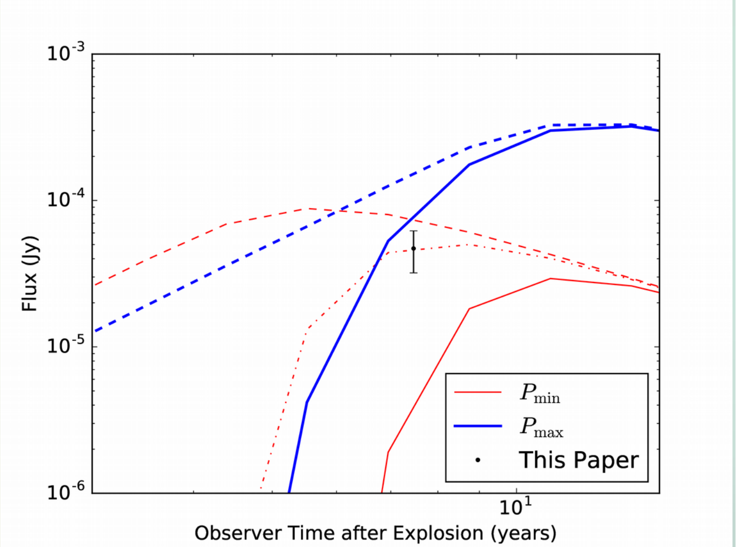
[a] Detection with peak flux density of 47 μJy.

PTF10hgi

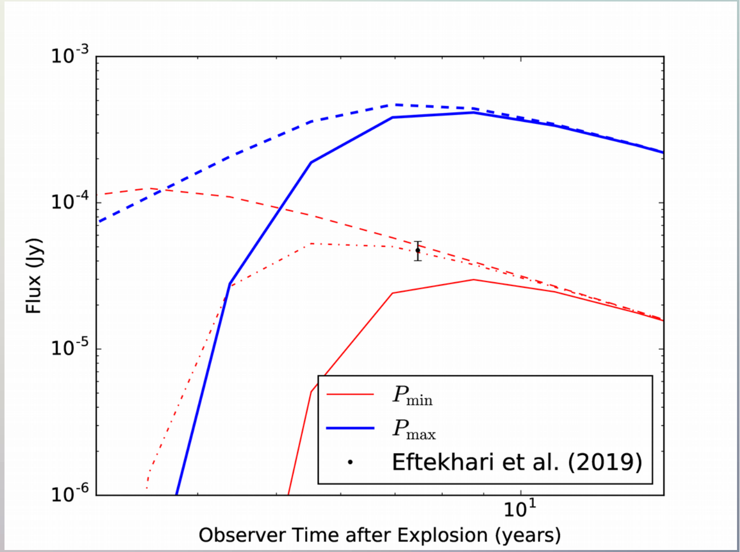


Law, Omand+ (2019)

3 GHz – 3.3σ detection

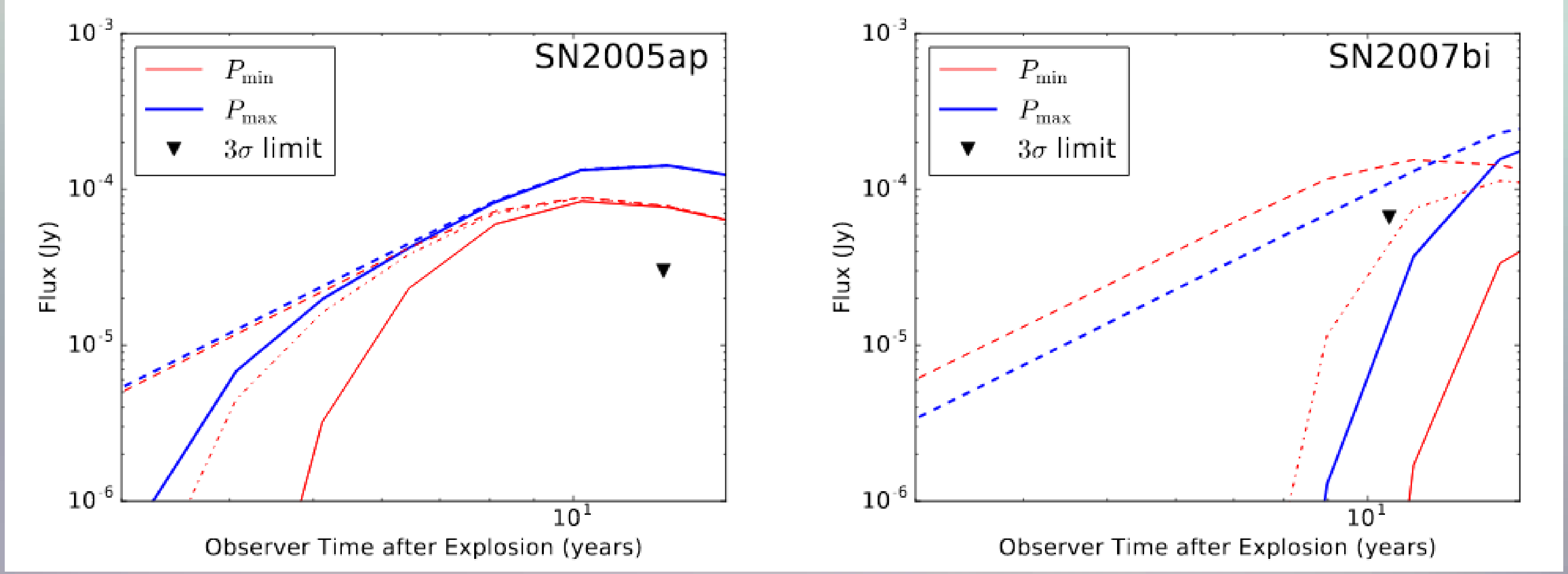


6 GHz – 6.7σ detection



VLA Non-detections

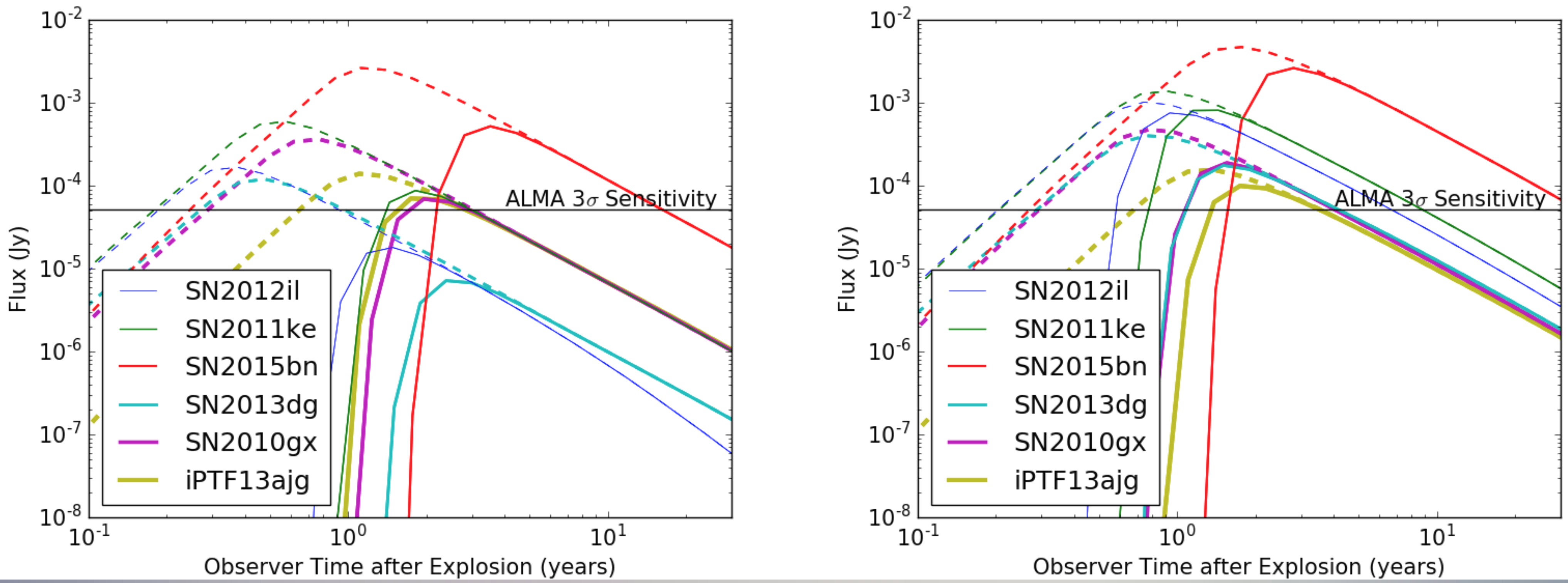
Name	$P_{\rm min}$ abs	$P_{\rm min}$ unabs	$P_{\rm max}$ abs	$P_{\rm max}$ unabs	$P_{\rm min}$ w/ PTF10hgi-like abs
SN2005ap	Excluded	Excluded	Excluded	Excluded	Excluded
SN2007bi	Viable	Excluded	Viable	Excluded	Viable
SN2006oz	Viable	Viable	Excluded	Excluded	Viable
PTF09cnd	Viable	Excluded	Viable	Excluded	Viable
SN2010kd	Viable	Excluded	Viable	Excluded	Viable
SN2010gx	Viable	Excluded	Excluded	Excluded	Excluded
PTF09cwl	Viable	Excluded	Viable	Excluded	Viable
SN2011ke	Viable	Excluded	Excluded	Excluded	Excluded
PTF09atu	Viable	Viable	Viable	Viable	Viable



Law, Omand+ (2019)

Predictions (100 GHz Radio emission)

P = 1 ms   P = P_{max}

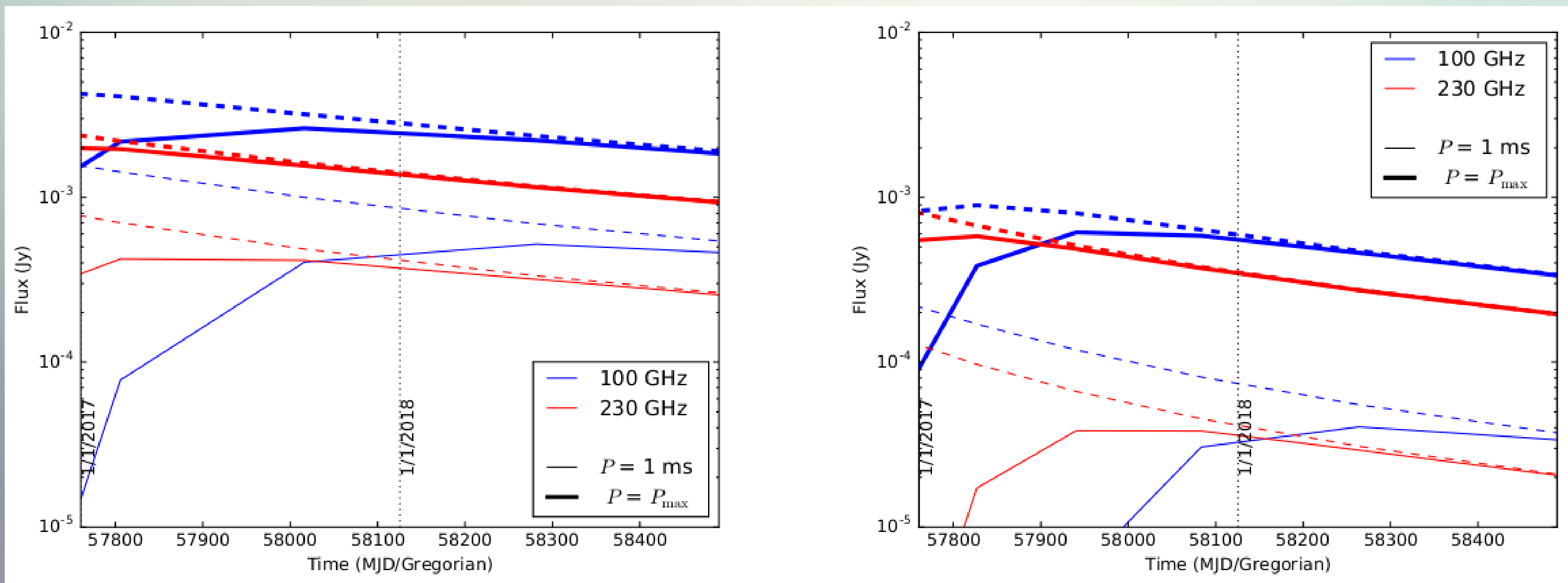


Omand+ (2018)

Submillimetre Targets

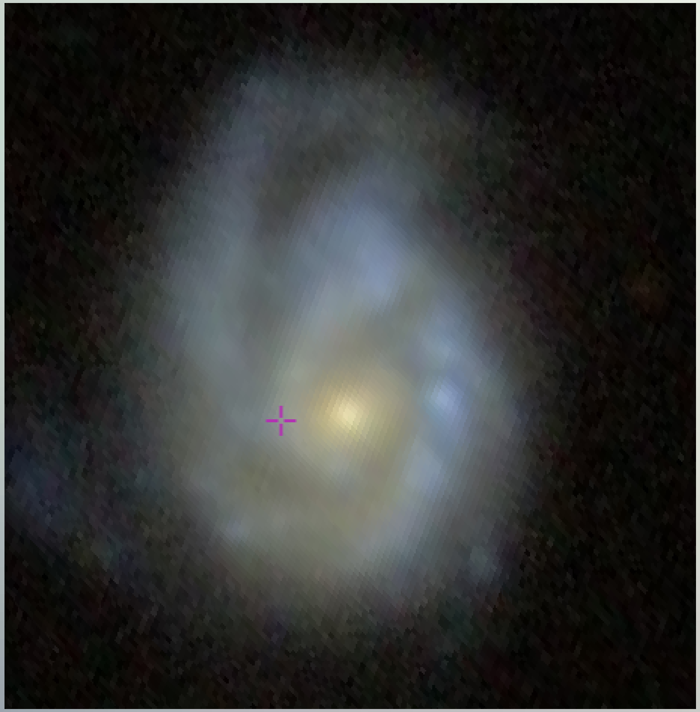
Name	redshift	RA	Dec	P_{-3}, B_{13}, $M_{\rm ej}$ (min)	P_{-3}, B_{13}, $M_{\rm ej}$ (max)
SN 2015bn	0.1136	11:33:41.57	+00:43:32.2	1.0, 2.1, 17	1.4, 1.0, 5
SN 2016ard	0.2	14:10:44.56	-10:09:35.42	1.0, 6.0, 12	2.2, 1.7, 1.5

Name	Redshift	RA	Dec	P_{-3}, B_{13}, $M_{\rm ej}$ (min)	P_{-3}, B_{13}, $M_{\rm ej}$ (max)
SN2017egm	0.030721	10:19:05.620	+46:27:14.08	1.0, 13.0, 11.5	2.0, 2.0, 2.0

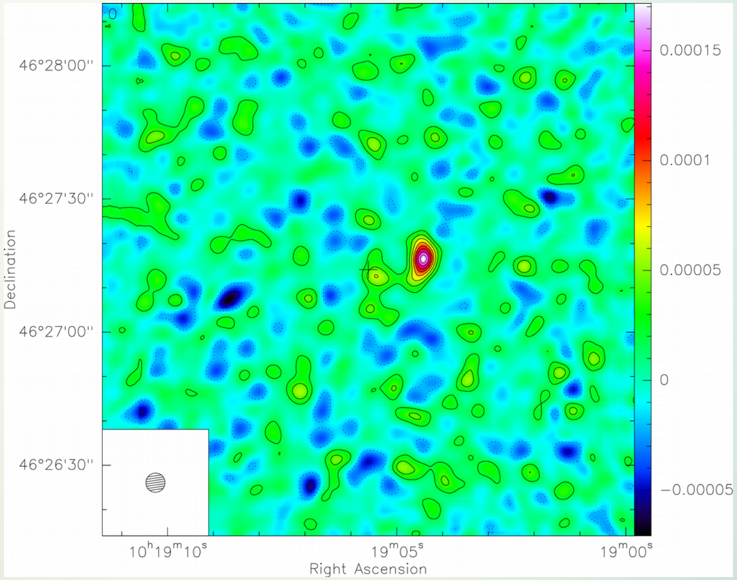


SN2015bn Predictions SN2016ard

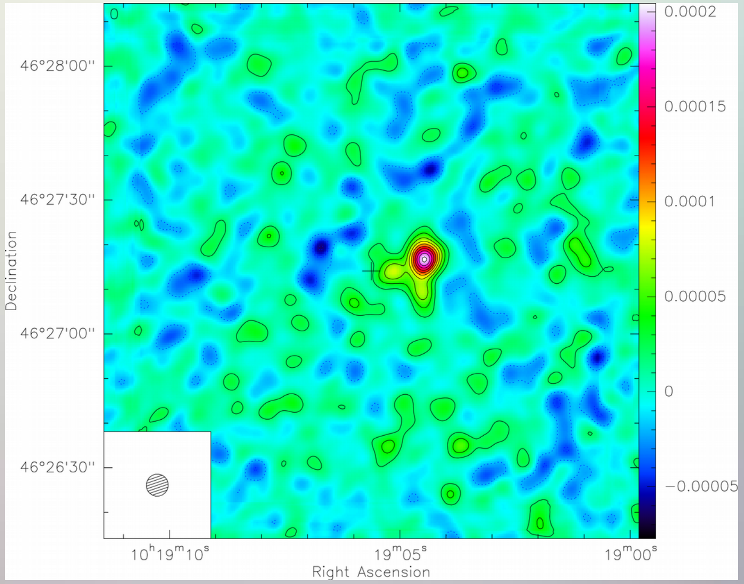
SN2017egm



Optical (SDSS)

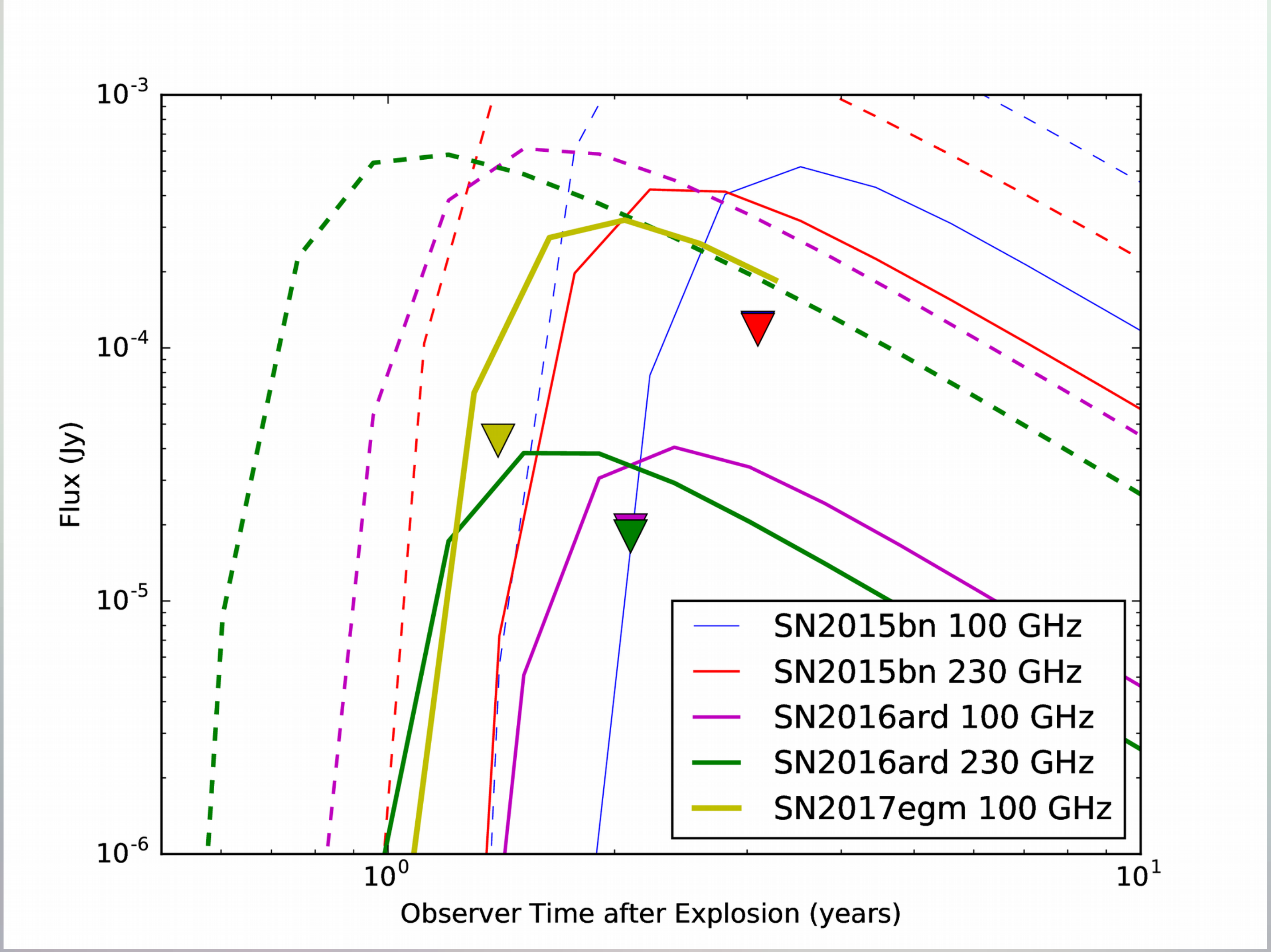


USB (101 GHz)



LSB (85 GHz)

Constraints



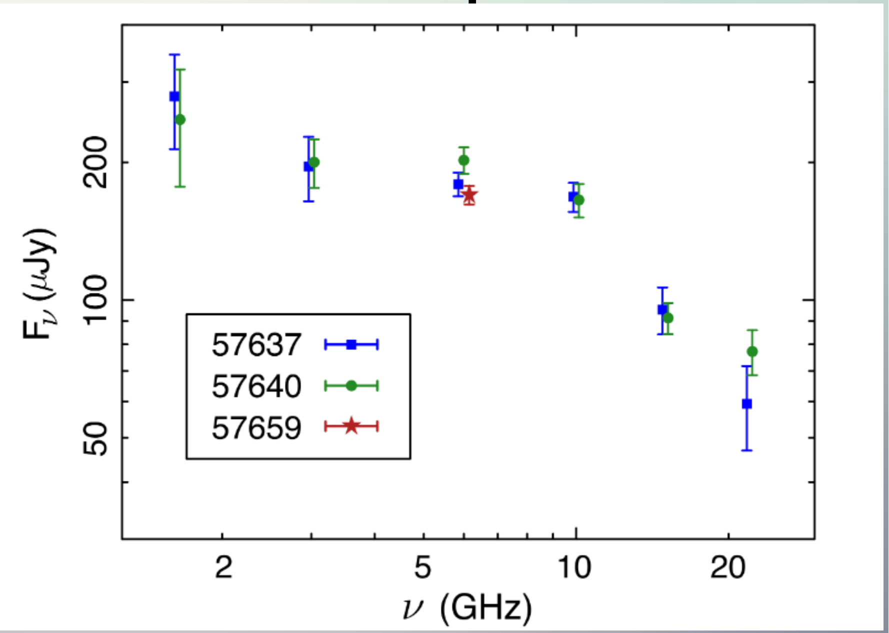
Murase, Omand+ (in prep)

Observational Summary

- 10 targets observed in radio:
  - 1 detection, consistent with model
  - 9 non-detections, 1 inconsistent with model
  - No FRBs found
- 3 targets observed in submillimetre:
  - 3 non-detections, all inconsistent with model
- Suggests problem with the model, either:
  - SLSNe are not pulsar driven
  - Ejecta is more heavily ionized than predictions
  - Electron injection spectrum is not Crab-like

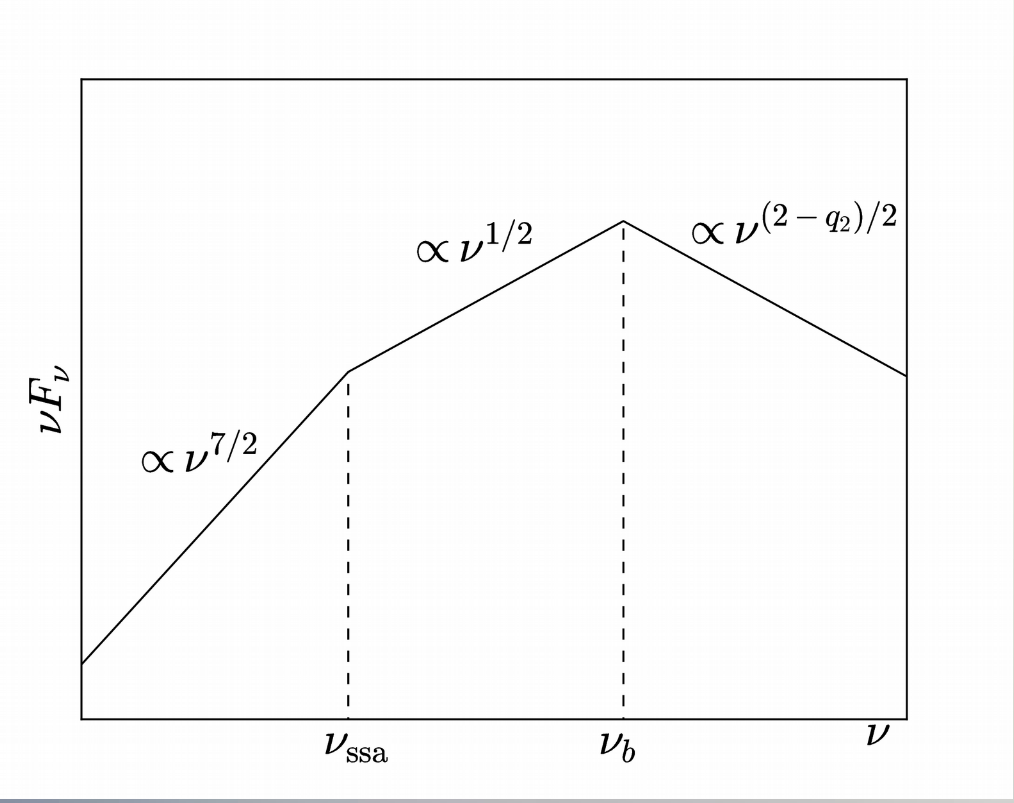
Adjusting the Model

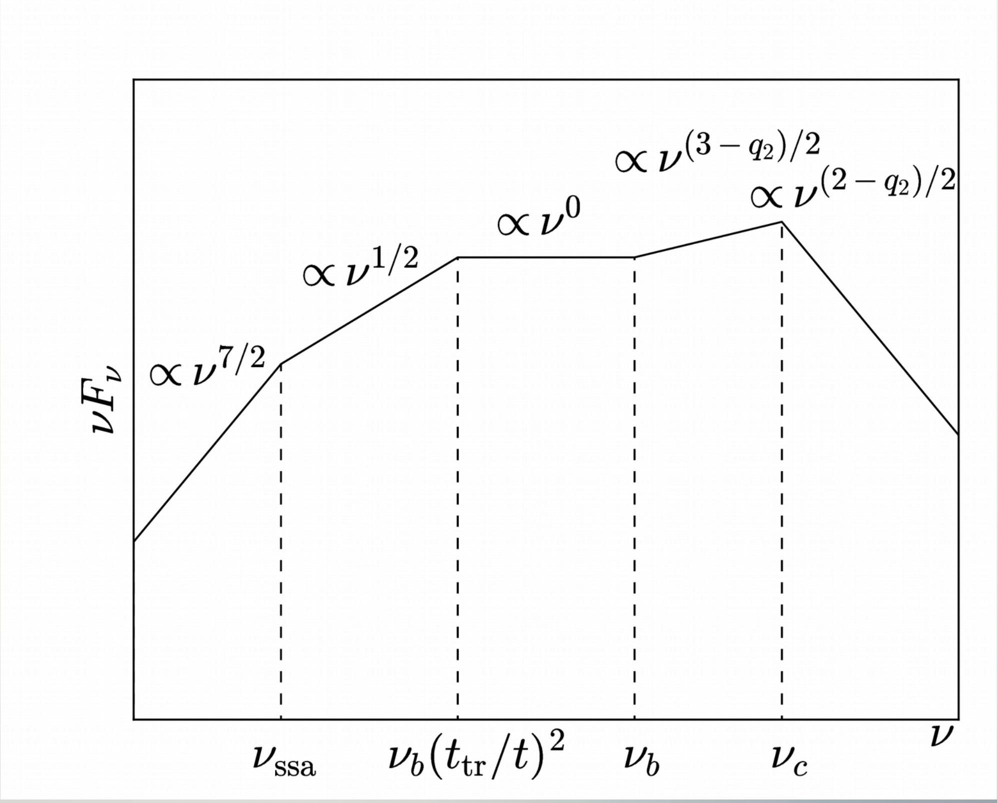
- Changing the injection spectrum to be sharply peaked may resolve theory/observation tension
- Hysteresis effects in the PWN evolution may become important for the relic electron spectrum
- FRB 121102 has a spectral break at 10 GHz
  – may be effect of relic electrons



Chatterjee+ (2017)

Analytical PWN Spectrum: Time Evolution





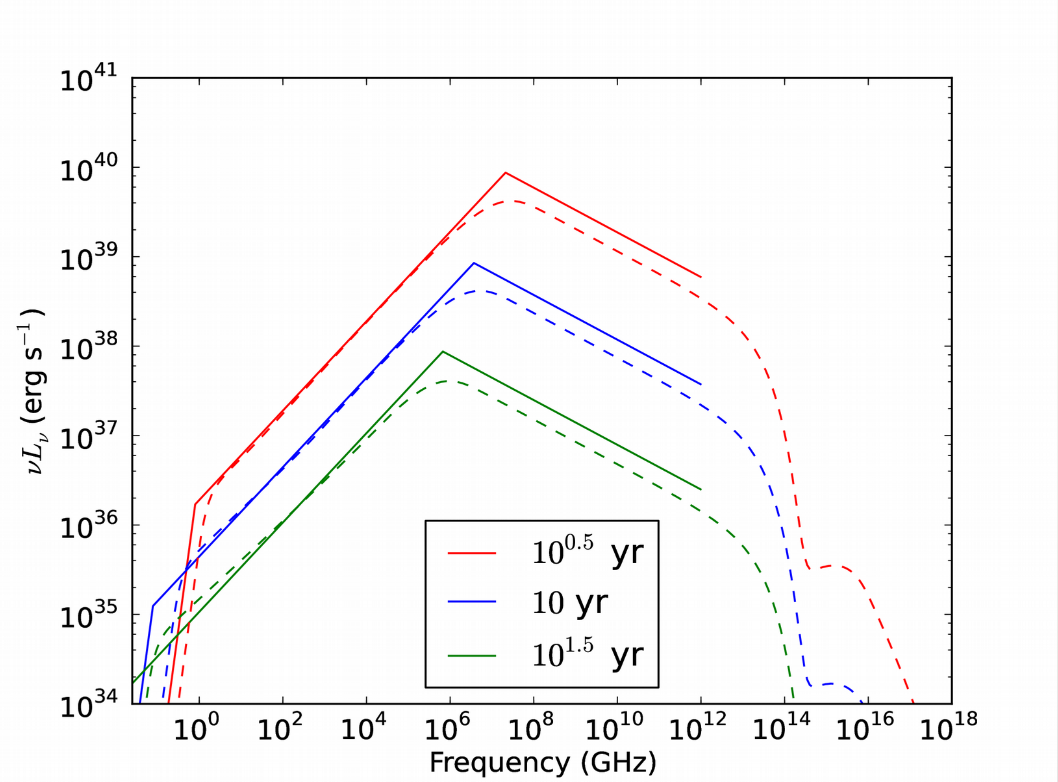
$t < t_{tr}$

$t > t_{tr}$

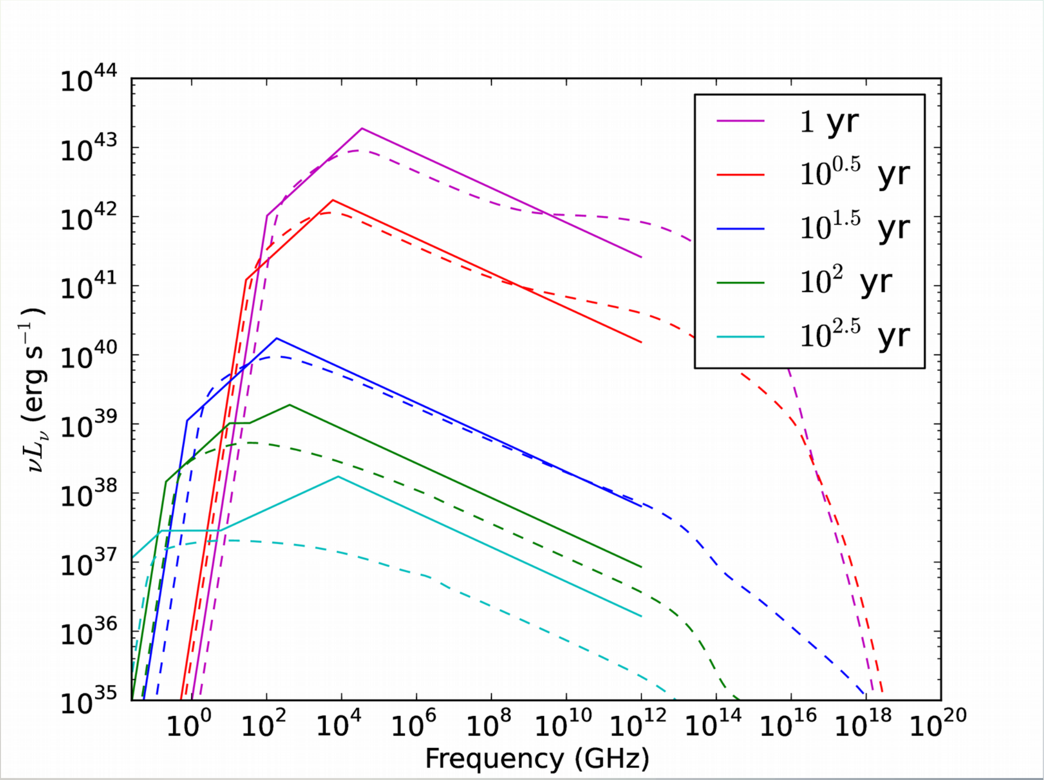
Omand+
(prelim)

Comparison to Numerical Results

Higher B, higher γ_b



Lower B, lower γ_b



Omand+ (prelim)

Analytical Model

- Pros
  - Much faster than numerical simulations
  - Works well for high B, high γ_b now, small fixes should achieve consistency at low B, low γ_b
  - Should be able to put constraints on PTF10hgi and FRB 121102
- Cons
  - Doesn’t account for ICS, pair-cascades
- Still To-Do
  - Implement SSA self-consistently
  - Solve Compton Y self-consistently
  - Figure out why there’s no peak in the spectrum at γ_c

Summary

- Radio/submillimetre predictions found several candidates for follow-up
- Radio observations got one detection – expected another PWN detection
- Submillimetre observations got no detections, three expected
- Revised model still needs work, but should be able to ease theory/observation tension