Radio and Submillimetre Constraints on the Pulsar-Driven Supernova Model

Conor Omand

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

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

Collaborators

Theory:

K. Kashiyama	Tokyo University
K. Murase	Penn State University

VLA:

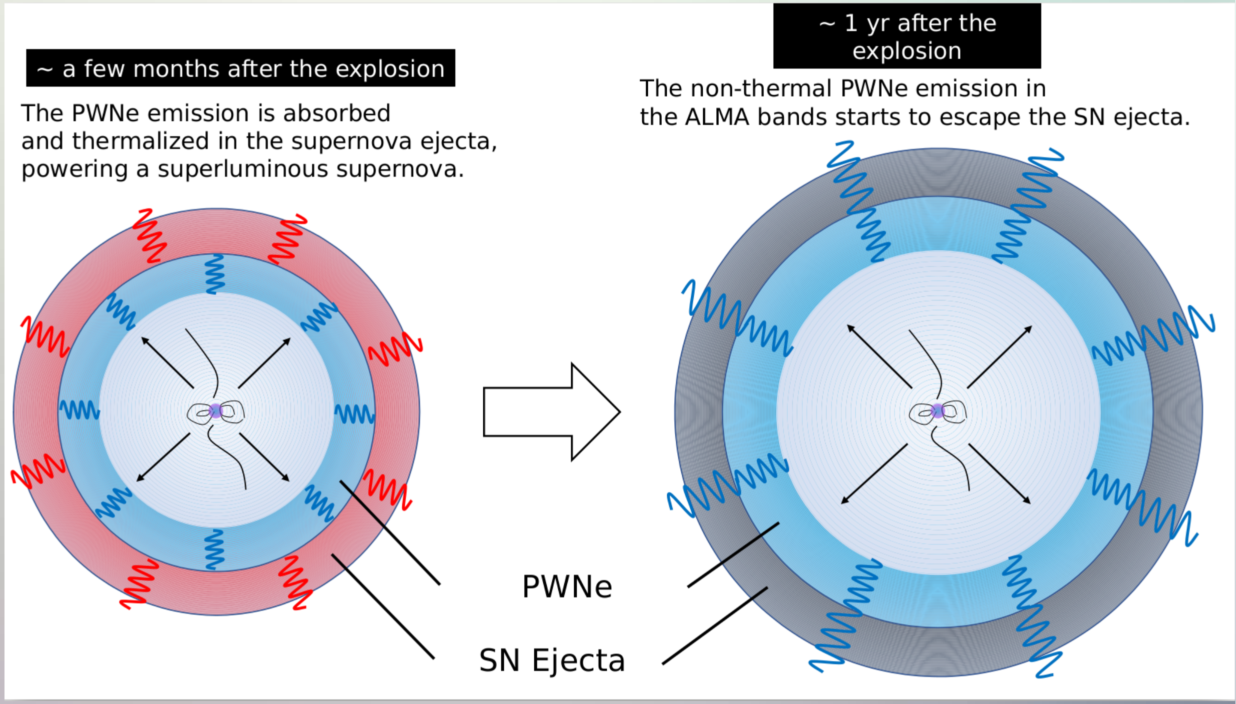
C. Law	UC Berkeley
K. Kashiyama	Tokyo University
K. Murase	Penn State University
G. Bower	Academica Sinica
K. Aggarwal	West Virginia University
S. Burke-Spolaor	NRAO
B. Butler	NRAO
P. Demorest	NRAO
T. Lazio	Caltech
J. Linford	West Virginia University
M. Rupen	DRAO

ALMA/NOEMA:

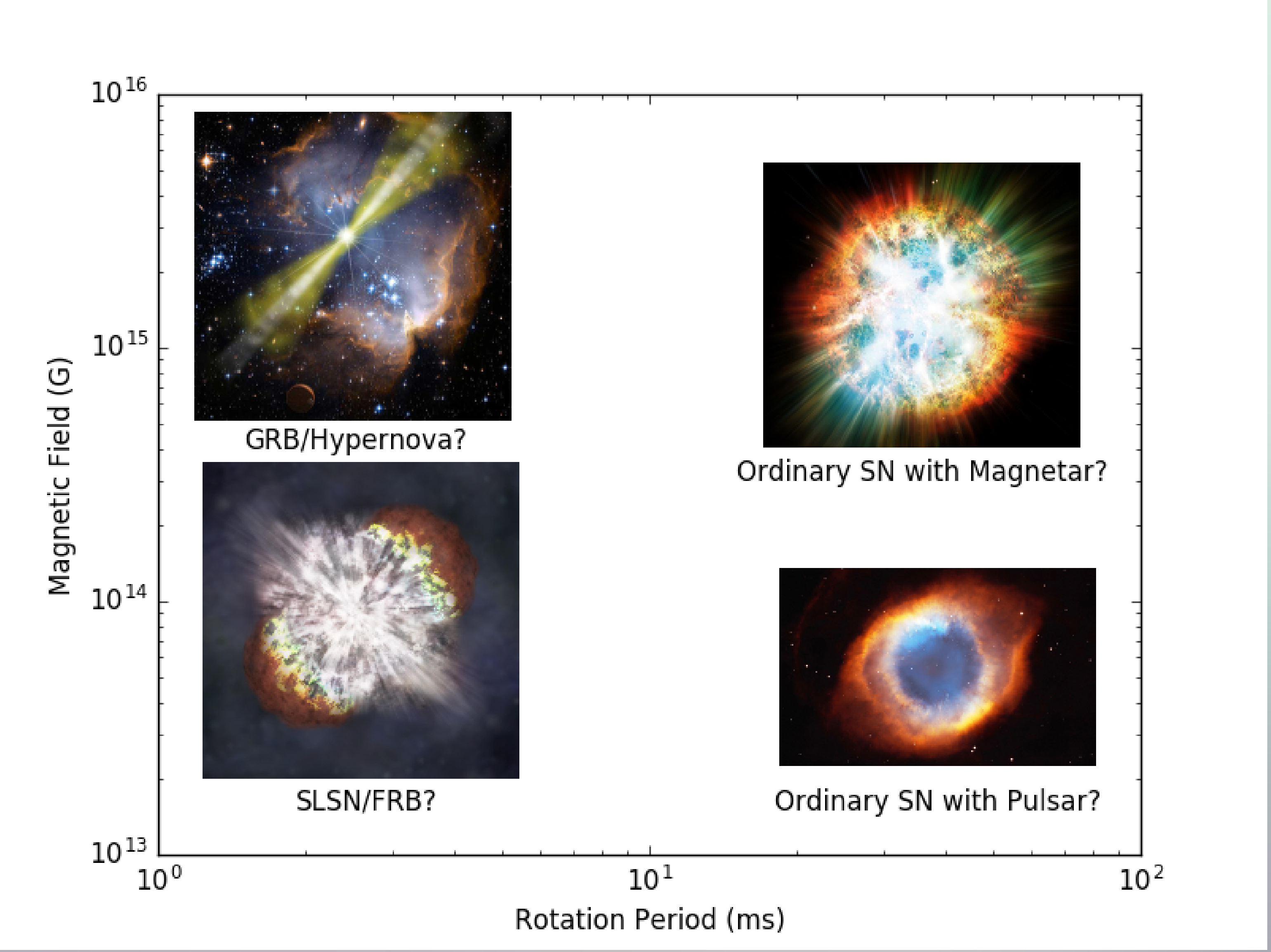
K. Murase	Penn State University
K. Kashiyama	Tokyo University
C. Law	UC Berkeley
G. Bower	Academica Sinica
H. Nagai	NAOJ
R. Margutti	Northwestern University
D. Coppejans	Northwestern University
G .Terreran	Northwestern University
E. Berger	Harvard University
R. Chornock	Ohio University
K. Alexander	Harvard Univeristy
M. Nicholl	University of Edinburgh
D. Fox	Penn State University
P. Mészáros	Penn State University

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 SLSNe, late-phase emission should be probed



A variety of Pulsar-Driven Transients

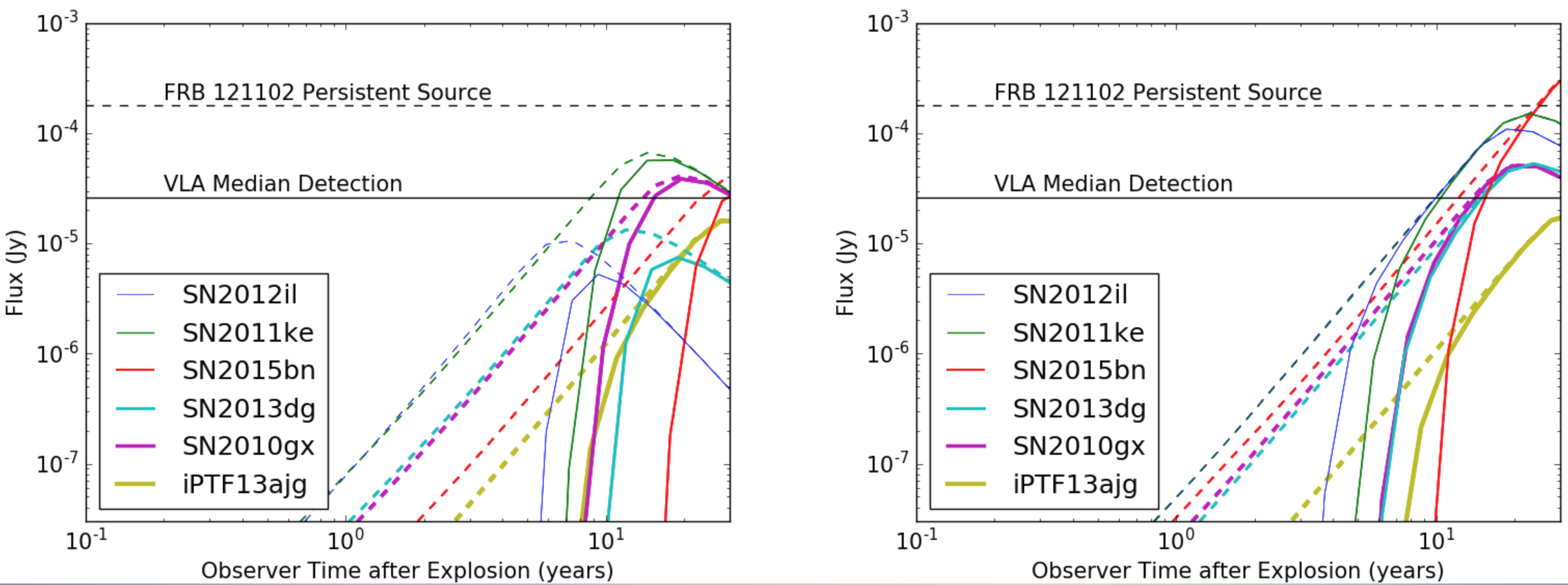


Strategy

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

Predictions (1 GHz Radio emission)

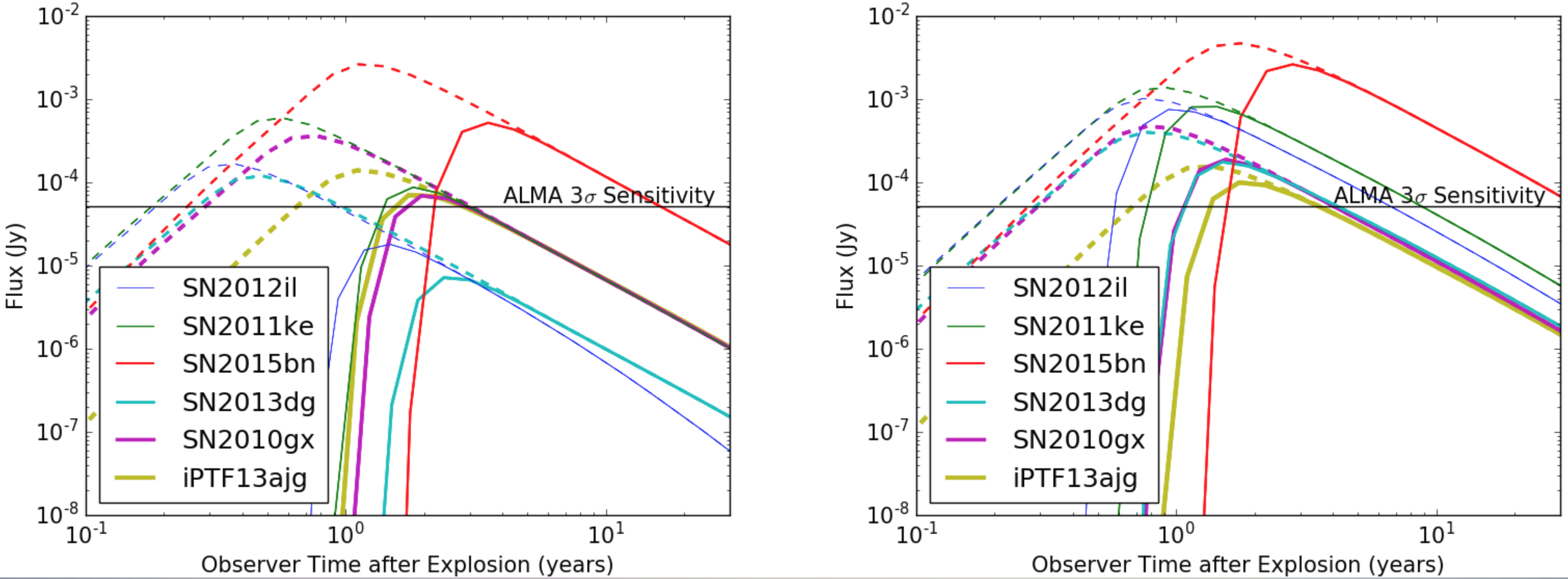
P = 1 ms　　　　　　$P = P_{max}$



Omand+ (2018)

Predictions (100 GHz Radio emission)

P = 1 ms P = P_{max}



Omand+ (2018)

VLA Targets

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[b]	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	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

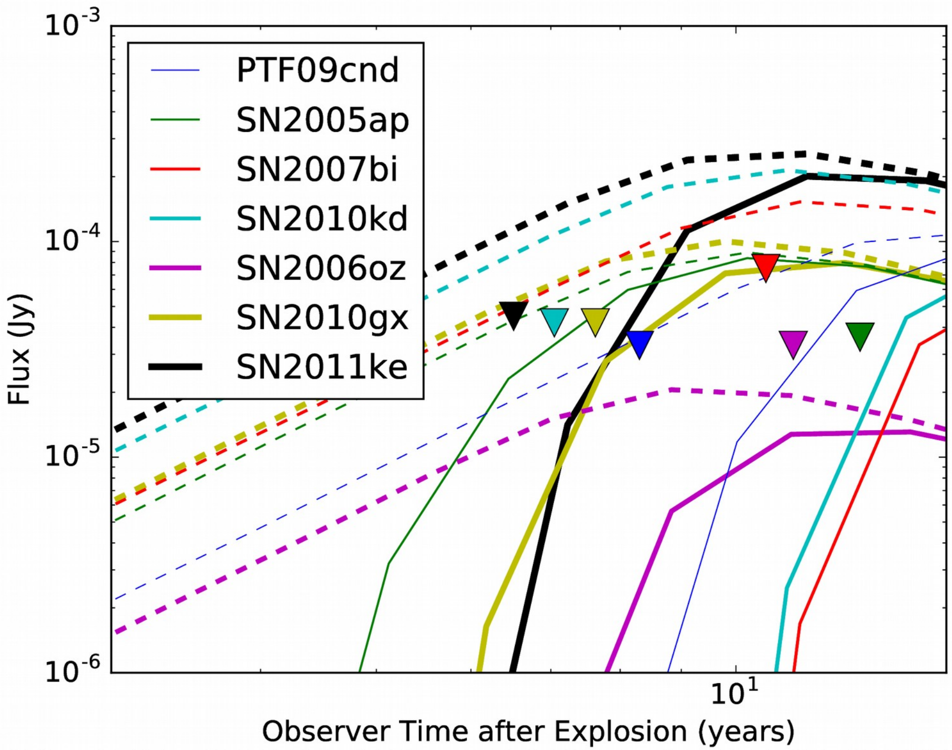
[a] Late-time radio limit at 1.4 GHz by Schulze et al. (2018).

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

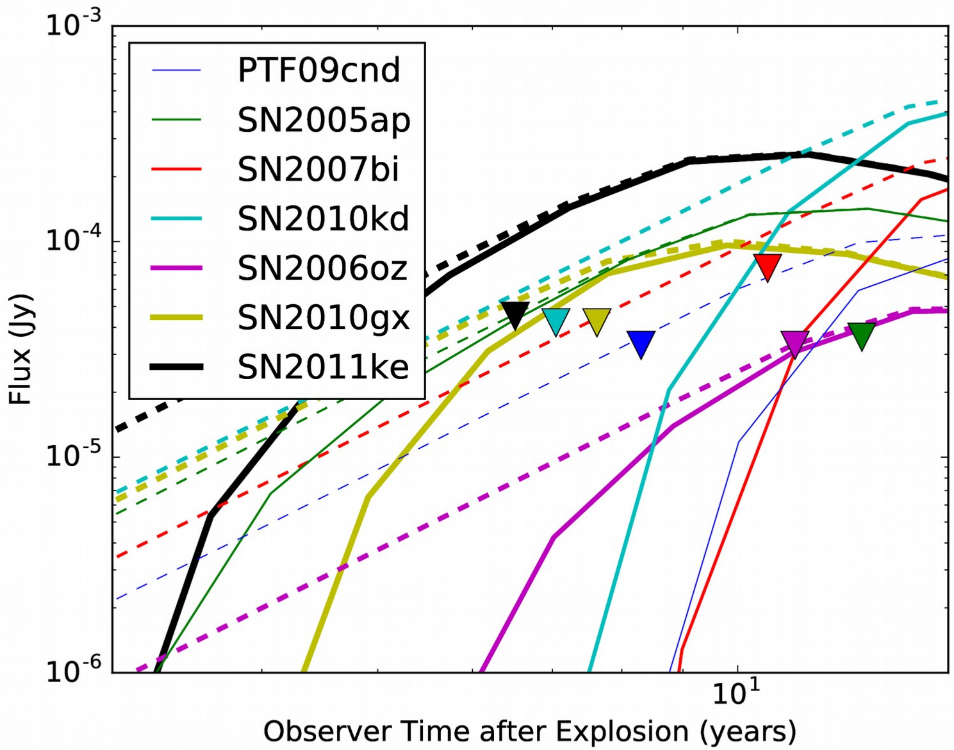
Name	Epoch (MJD)	Observing time (min)	Sensitivity (μJy beam^{-1}; 1σ)
SN 2005ap	58060	28.5	12
	58131	28.5	15
SN 2007bi	58074	17.2	25
	58128	17.2	27
SN 2006oz	58036	30.3	11
	58124	30.3	12
PTF10hgi	58045	13.2	19
	58130	13.2	22
PTF09cnd	58045	23.4	12
	58130	23.4	11
SN 2010kd	58074	13.8	14
	58128	13.8	31
SN 2010gx	58074	20.6	14
	58128	20.6	16
PTF09cwl	58060	36.5	9
	58131	36.5	20
SN 2011ke	58060	17.6	15
	58131	17.6	18
PTF09atu	58045	54.7	12
	58130	54.7	9

VLA Non-detections

P = 1 ms



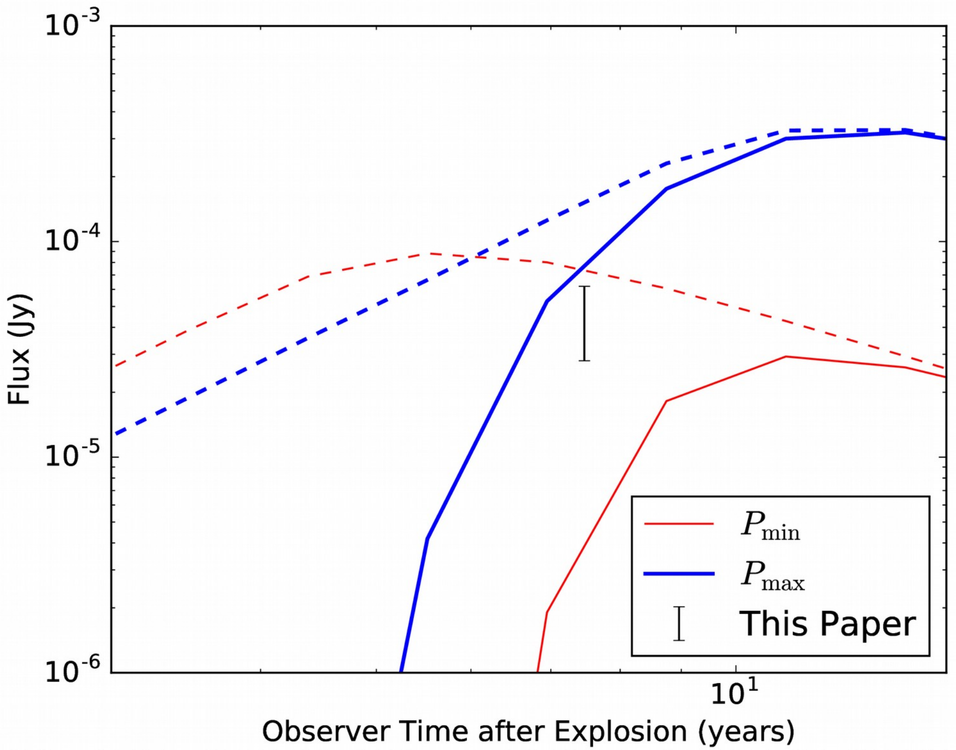
$P = P_{max}$



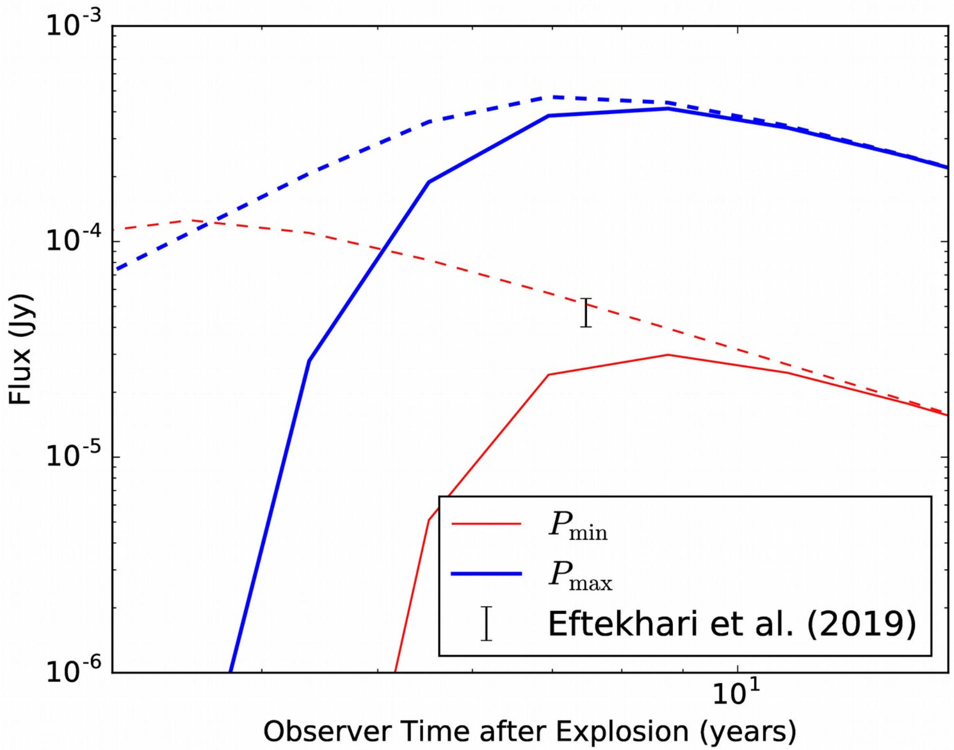
Law, Omand+ (in prep)

PTF10hgi

3 GHz – 2.6σ detection



6 GHz – 6.7σ detection



Law, Omand+ (in prep)

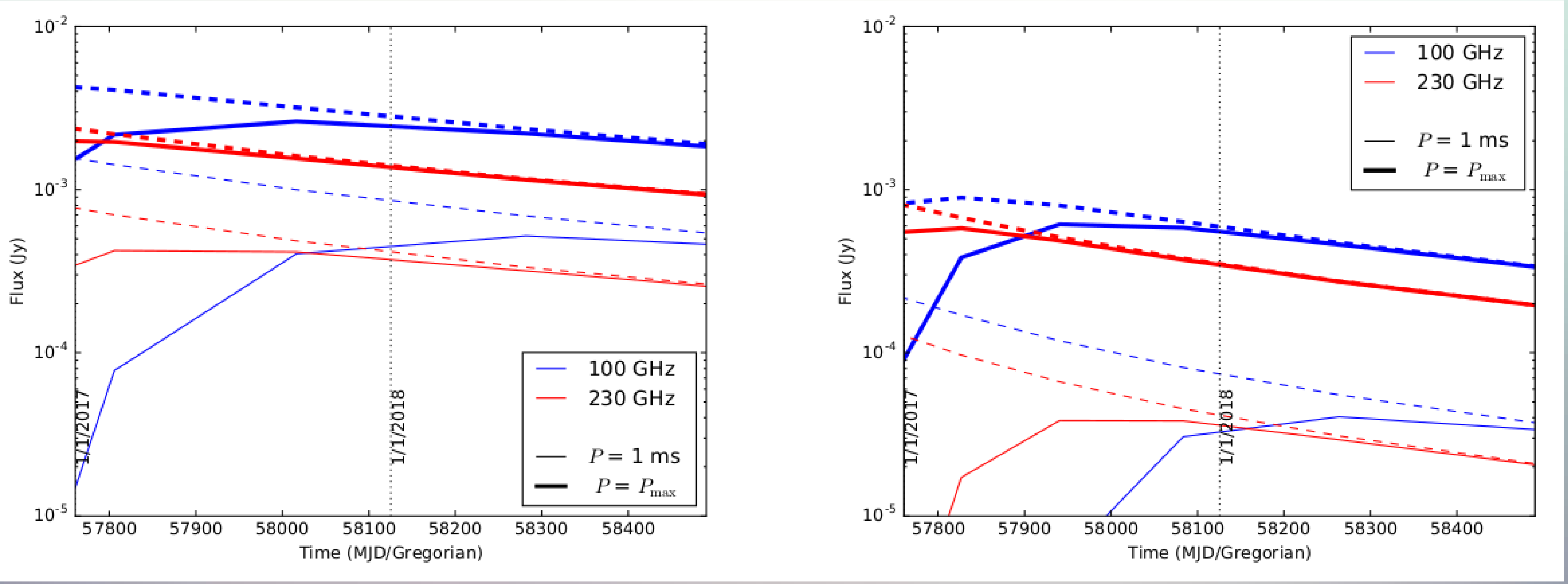
VLA Observations Summary

- 9 non-detections and 1 marginal detection
- No FRBs found
- A few pulsar parameters constrained by non-detections
- SN2005ap should have been detected if our model/predictions were correct
- PTF10hgi consistent with models – more work needed to determine pulsar parameters

Submillimetre Targets

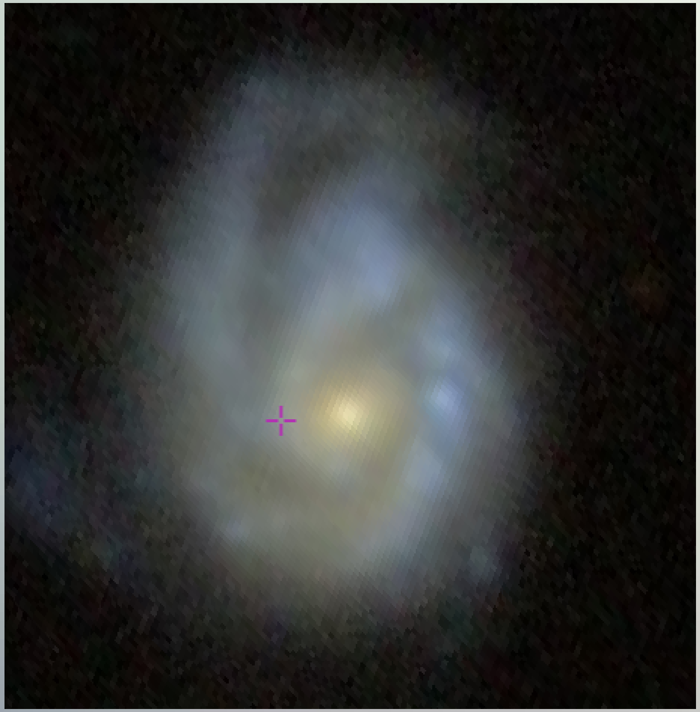
Name	redshift	RA	Dec	P_{-3}, B_{13}, $M_{\rm ej}$ (min)	P_{-3}, B_{13}, $M_{\rm ej}$ (max)
SN 2015bn	0.1136	11:33:41.57	+00:43:32.2	1.0, 2.1, 17	1.4, 1.0, 5
SN 2016ard	0.2	14:10:44.56	-10:09:35.42	1.0, 6.0, 12	2.2, 1.7, 1.5

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

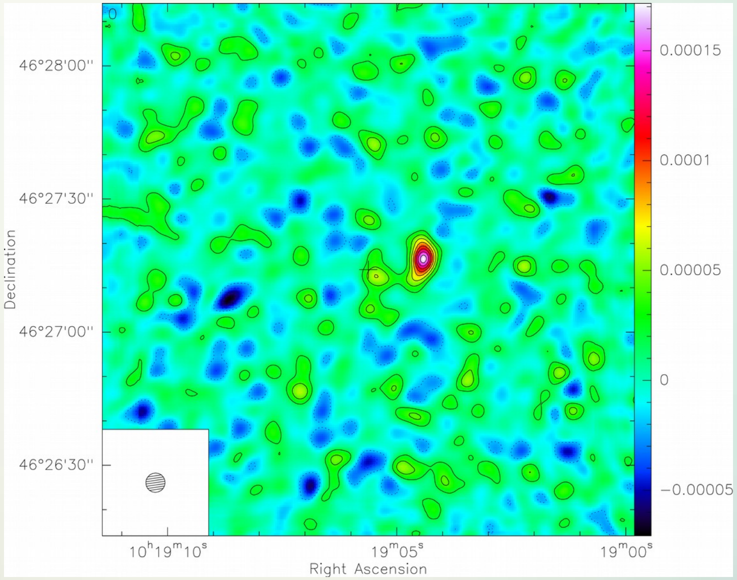


SN2015bn Predictions SN2016ard

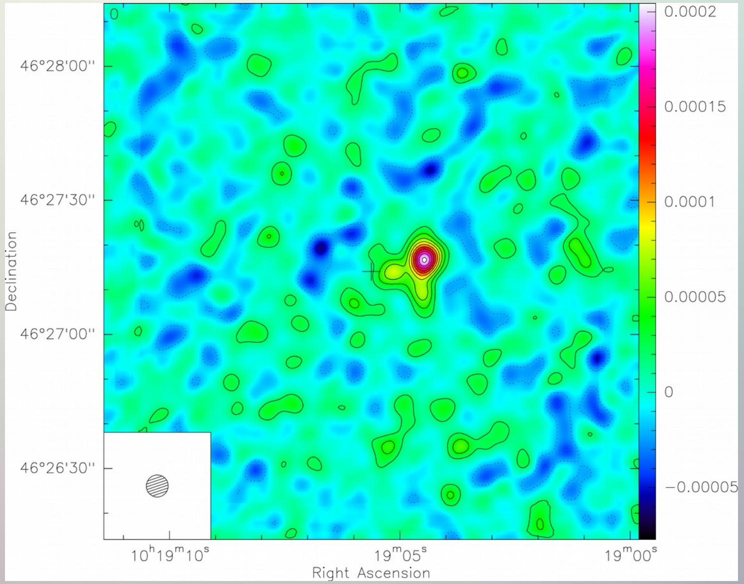
SN2017egm



Optical (SDSS)

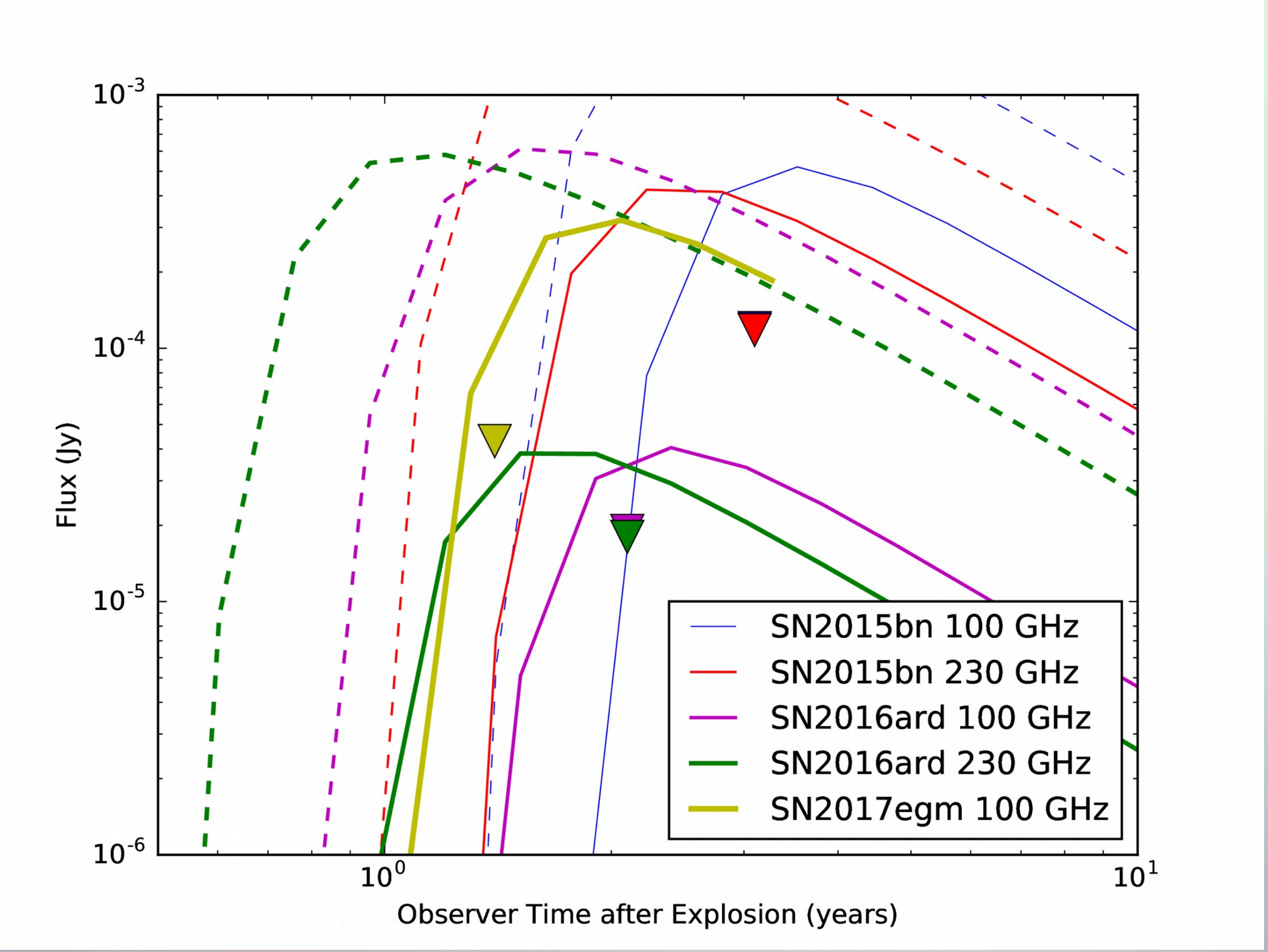


USB (101 GHz)



LSB (85 GHz)

Constraints



Murase, Omand+ (in prep)

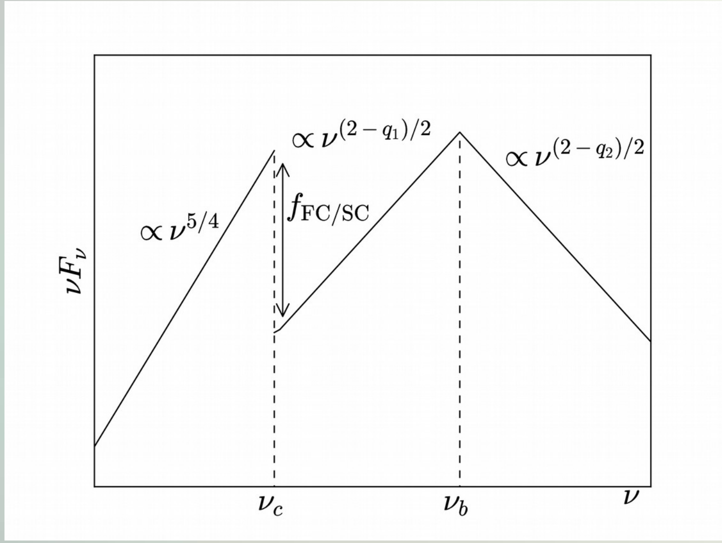
Submillimetre Summary

- 3 Non-detections below P_{min} expectations
- 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
- Third seems most likely, and easiest to correct

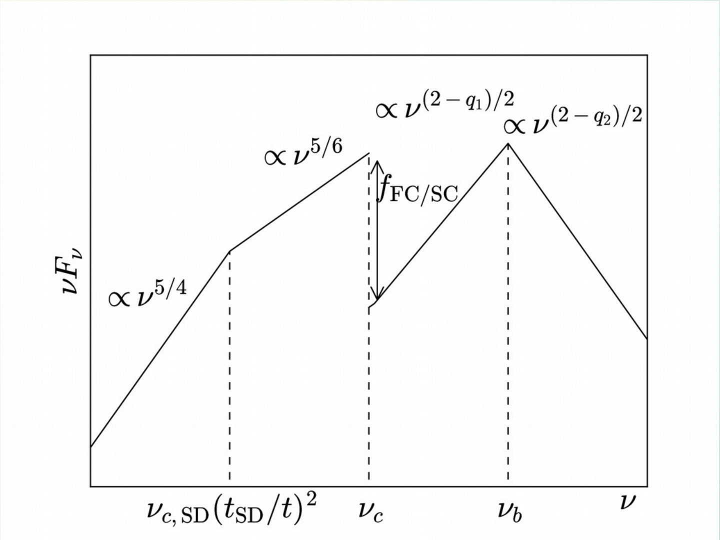
Changing the Model

- 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
- Analytical derivation will give us spectral indices – useful to diagnose future numerical calculations

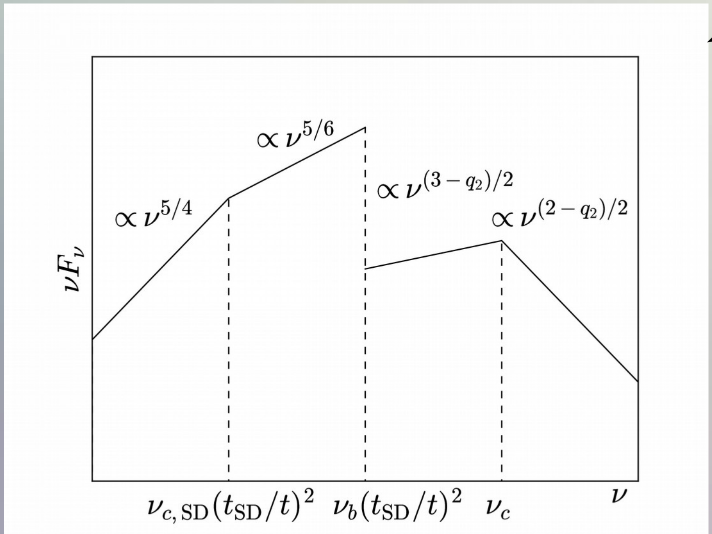
Analytical PWN Spectrum: Time Evolution



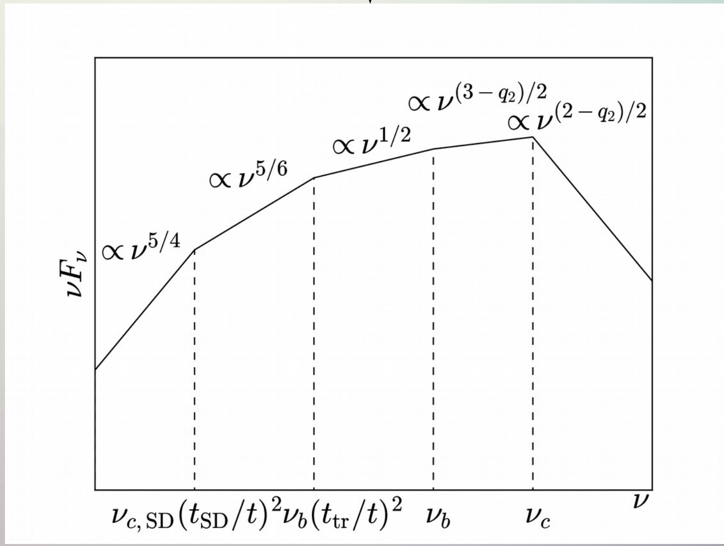
$t < t_{SD} < t_{tr}$



$t_{SD} < t < t_{tr}$



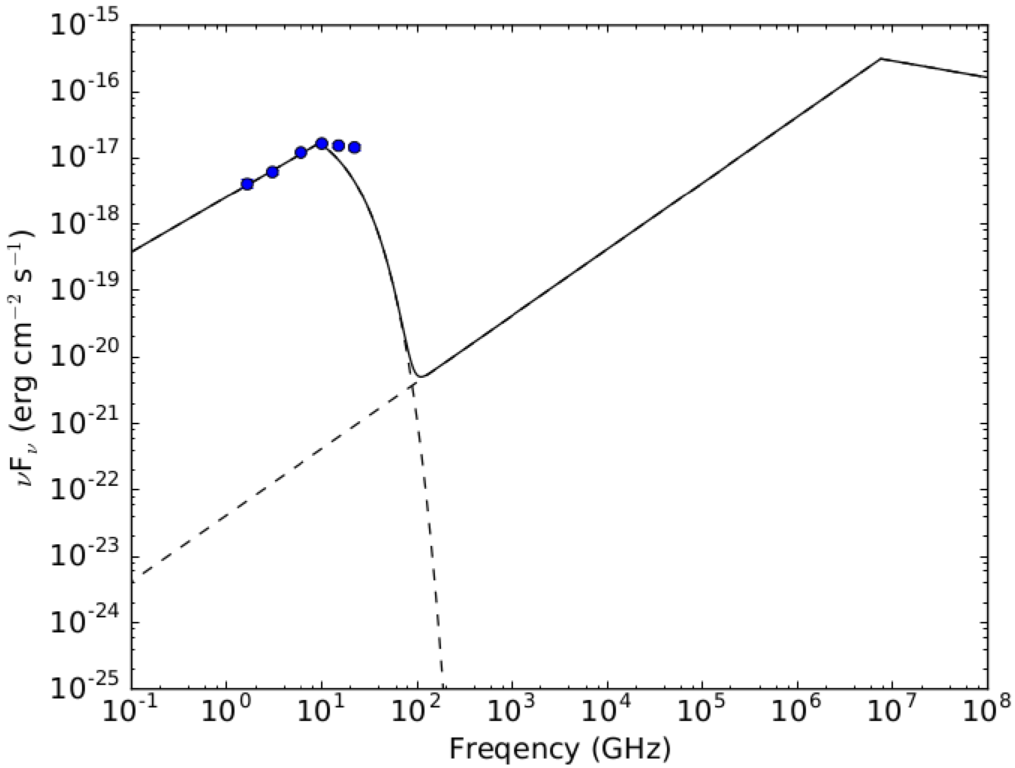
$t_{SD} < t_{tr} < t$
($\mu_\pm$ constant)



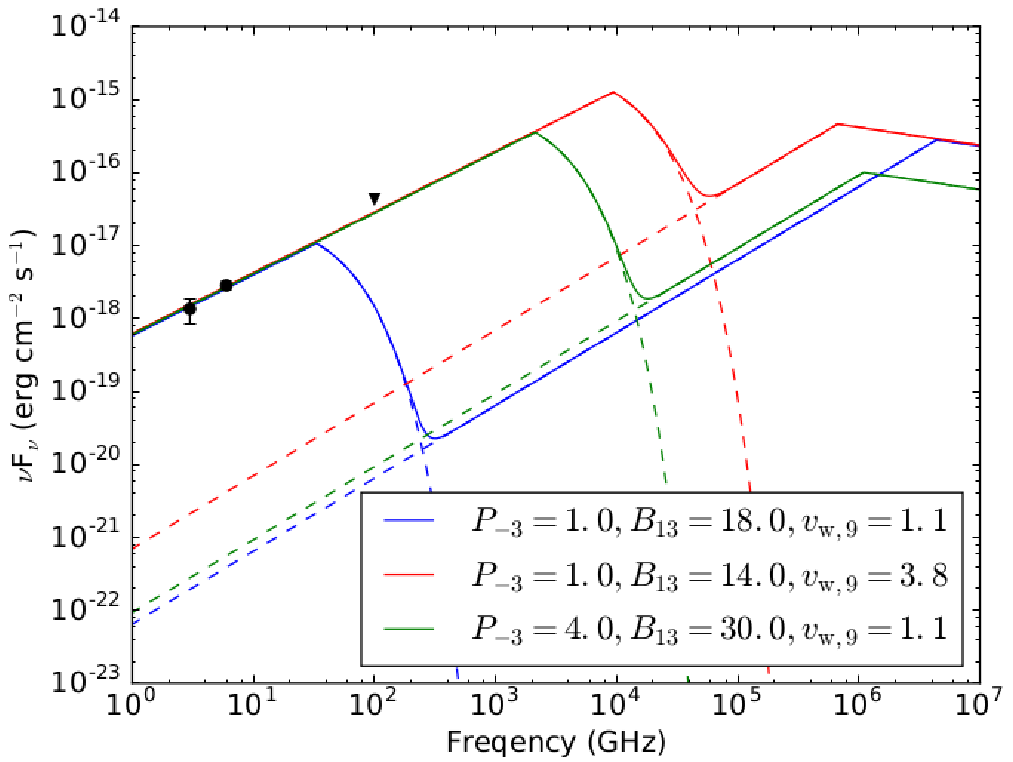
$t_{SD} < t_{tr} < t$
(γ_b constant)

Omand+
(in prep)

Fitting the Sources



FRB 121102



PTF10hgi

Omand+ (in prep)

Summary

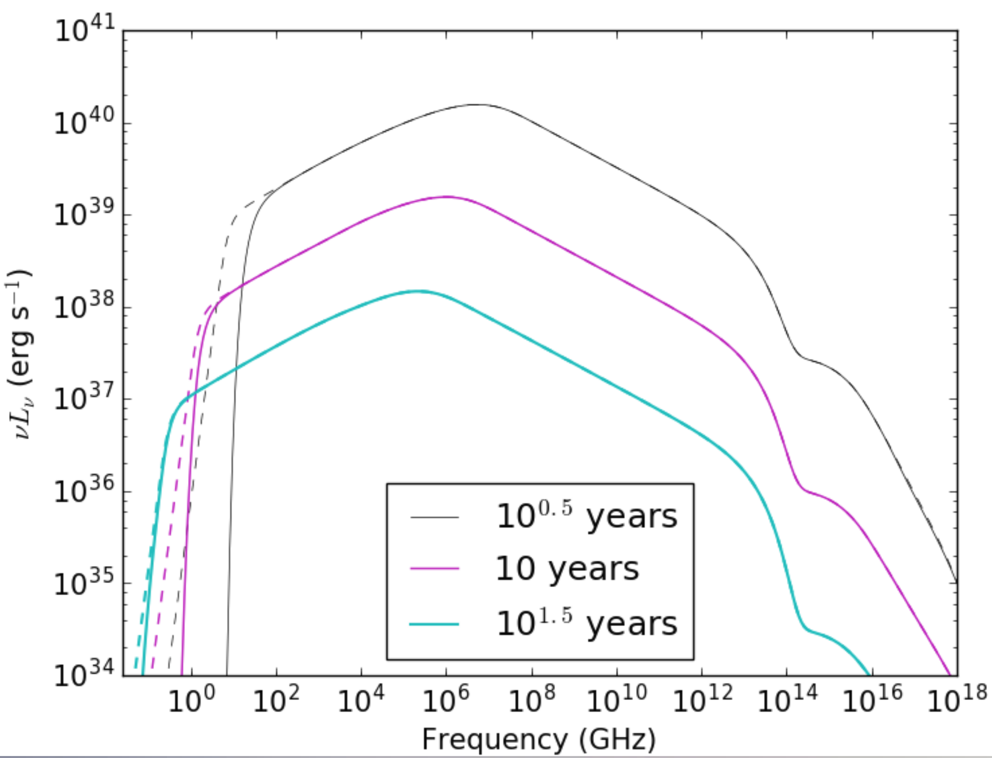
- Radio/submillimetre predictions found several candidates for follow-up
- Radio observations got one marginal detection – expected another PWN detection
- Submillimetre observations got no detections, three expected
- Revised model can fit spectral break in FRB 121102, consistent with PTF10hgi

A week of

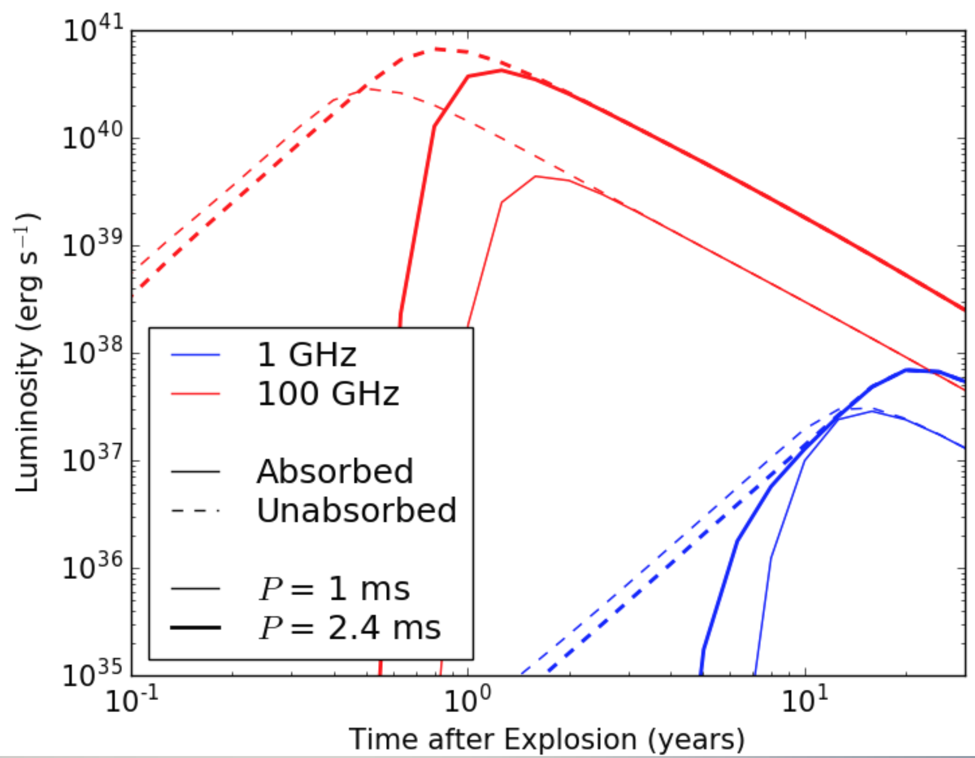
friends and FOEs

Predictions (Radio emission)

Broadband Spectra



Intrinsic Light Curves



Omand+ (2018)

Analytical PWN Spectrum: Overview

- Most electrons injected above γ_b

$$\frac{d\dot{N}_e}{d\gamma_e} = \frac{\epsilon_e L_{\rm SD}(t)}{\mathcal{R}_{b,e} m_e c^2 \gamma_b(t)} \begin{cases} (\gamma_e/\gamma_b(t))^{-q_1} & (\gamma_e < \gamma_b(t)), \\ (\gamma_e/\gamma_b(t))^{-q_2} & (\gamma_e > \gamma_b(t)). \end{cases}$$

- All electrons above γ_c cooled, become relic electrons
- γ_c increases with time, becomes larger than γ_b at t_{tr}
- Two extreme cases: γ_b constant, or $\mu_{\pm}$ constant

Analytical PWN Spectrum: Key Values

$$\nu_b = \frac{3}{4\pi}\gamma_b^2 \frac{eB_{\rm PWN}}{m_{\rm e}c},$$

$$\approx 2.98 \times 10^9 \epsilon_{B,-3}^{1/2} v_{\rm w,9}^{-3/2} B_{13}^3 P_{-3}^{-4} \gamma_{b,5}^2 \times \begin{cases} (t/t_{\rm SD})^{-1} & (t < t_{\rm SD}) \\ (t/t_{\rm SD})^{-3/2} & (t > t_{\rm SD}) \end{cases} \ {\rm GHz.}$$

$$\nu P_\nu(\nu_b) \approx 4.3 \times 10^{45} \epsilon_e B_{13}^2 P_{-3}^{-4} (1+Y)^{-1} \mathcal{R}_{b,e}^{-1} f_{\rm SD}(t) \ {\rm erg/s}$$

$$\nu_c = 0.69 \epsilon_{B,-3}^{-3/2} v_{\rm w,9}^{9/2} B_{13}^{-5} P_{-3}^{8} \begin{cases} (t/t_{\rm SD}) & (t < t_{\rm SD}), \\ (t/t_{\rm SD})^{5/2} & (t > t_{\rm SD}) \end{cases} \ {\rm MHz.}$$

$$\nu P_\nu(\nu_c) \approx 3.12 \times 10^{44} \epsilon_{B,-3}^{-1} B_{13}^{-2} P_{-3}^{2} v_{\rm w,9}^{3} \mathcal{R}_{b,e}^{-1} \times \begin{cases} (t/t_{\rm SD}) & (t < t_{\rm SD}), \\ (t/t_{\rm SD})^{-1} & (t > t_{\rm SD}) \end{cases} \ {\rm erg/s} \ .$$