LATE-TIME RADIO AND MILLIMETER OBSERVATIONS OF SUPERLUMINOUS SUPERNOVAE AND LONG GAMMA-RAY BURSTS

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Implications for Central Engines and Fast Radio Bursts

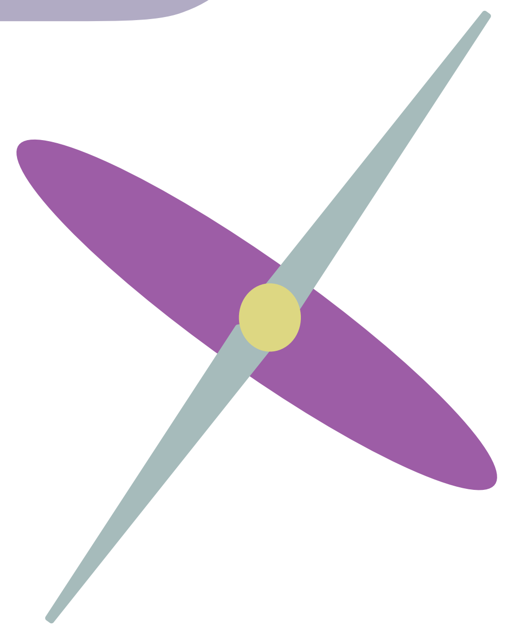
Superluminous supernovae (SLSNe) are a newly discovered class of supernovae that appear up to 100 times brighter than ordinary supernovae. These events occur as the cores of massive stars collapse at the end of their lifetimes. A specific class of SLSNe, dubbed "Type-I" SLSNe, refer to events that show no evidence for hydrogen in their **spectra**. Despite a growing sample size of events, the energy sources responsible for powering SLSNe remain a topic of debate.

Astronomers use spectra, which show the intensity of light emitted from a source over a range of wavelengths, to identify key elements present in the source.

Long-duration gamma-ray bursts (LGRBs) are among the most violent explosions in the universe, releasing **gamma-ray radiation** over a period of several seconds to a few minutes following the core-collapse of massive stars. However, similar to SLSNe, what remains following the star's collapse remains an open question.

Gamma-ray radiation is electromagnetic radiation, just like visible light that humans are sensitive to. Gamma-rays are a million times more energetic than photons from visible light!

Although both SLSNe and LGRBs are believed to occur following the core-collapse of massive stars, the precise physical mechanisms and sources of energy that produce the observed emission are not well understood. However, a number of similarities between the two events suggest that they may share a common origin.



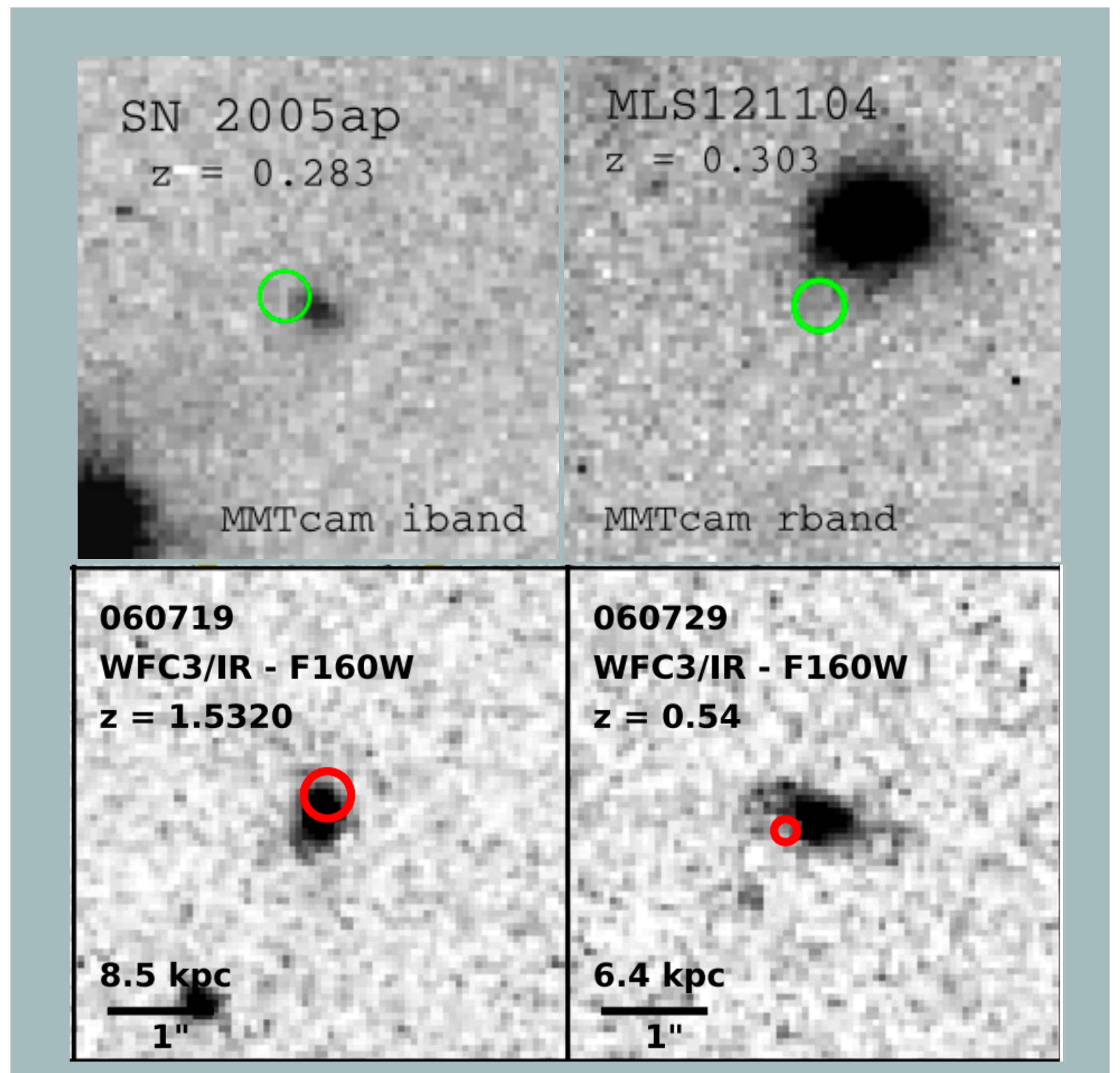


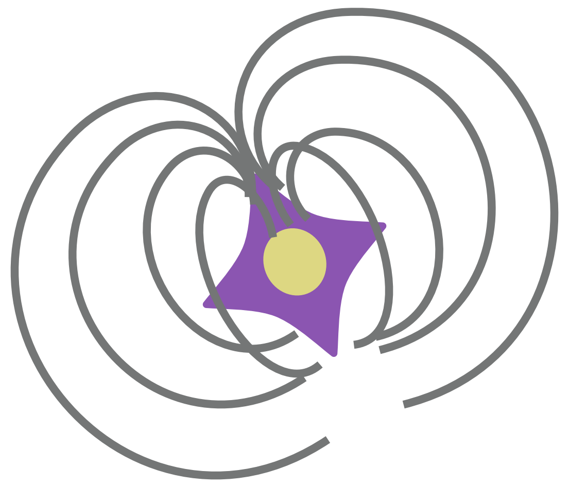
Figure 1: SLSNe host galaxies *(top)* and LGRB host galaxies *(bottom)* are preferentially irregular, low-metallicity, low-luminosity, star-forming dwarf galaxies. (Lunnan et al. 2014, Blanchard et al. 2016)

Key Open Question:

What are the energy sources that give rise to the observed emission from SLSNe and LGRBs?

The Clues:

- *Both SLSNe and LGRBs exhibit a preference for faint, low-metallicity dwarf galaxies (Fig. 1)*
- *Both show similar features in their spectra*
- *Both are associated with the deaths of massive stars*



*Increasing evidence that SLSNe and LGRBs are powered by **magnetars**!*

SUPERLUMINOUS SUPERNOVAE AND LONG GAMMA-RAY BURSTS FROM MAGNETARS

Magnetars are highly magnetized **neutron stars**, which are the dense cores left behind after a massive star explodes in a supernova.

A growing line of evidence suggests that both SLSNe and LGRBs are powered by magnetar central engines. While observations at optical and ultraviolet wavelengths probe the early-time emission from the supernova explosion, ***clear signatures of magnetar engines may be more readily detected in the radio and millimeter regimes.***

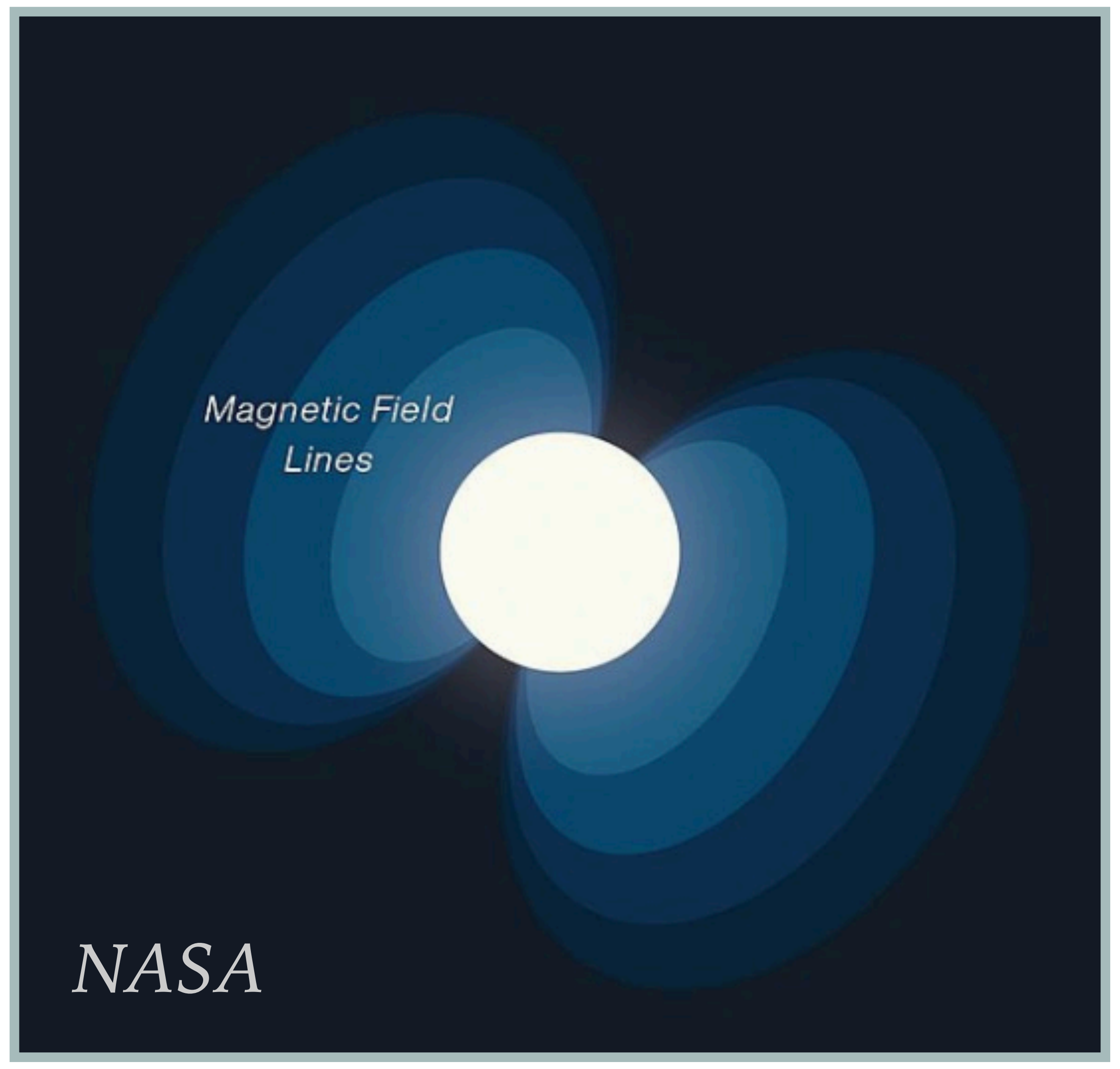


Figure 2: Artist's rendition of a magnetar; a dense core of neutrons surrounded by strong magnetic field lines.

FAST RADIO BURSTS FROM MAGNETARS

More evidence emerged in favor of a ***possible connection between SLSNe, LGRBs, and magnetars*** with the discovery and localization of the first repeating **fast radio burst** FRB 121102, which was localized to a dwarf galaxy, reminiscent of the host galaxies of SLSNe and LGRBs. In addition to the host identification, the source was further associated with a compact source of radio emission several light years across. ***Such radio nebulae are predicted to accompany magnetars on timescales of several years post-explosion***, as the supernova ejecta becomes transparent to radio emission. This combination of properties has prompted theories suggesting that FRBs are produced by young magnetars born in SLSN and/or LGRB explosions.

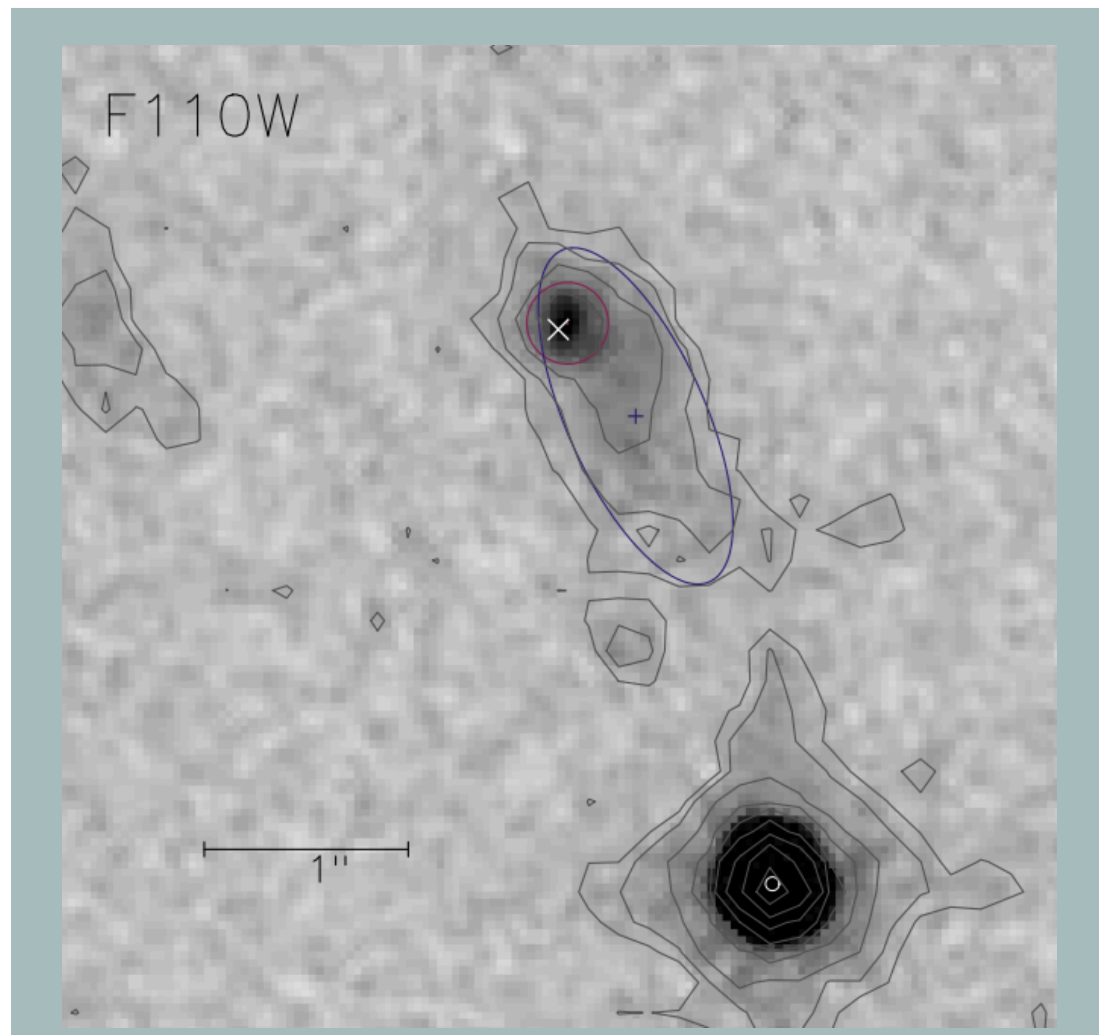
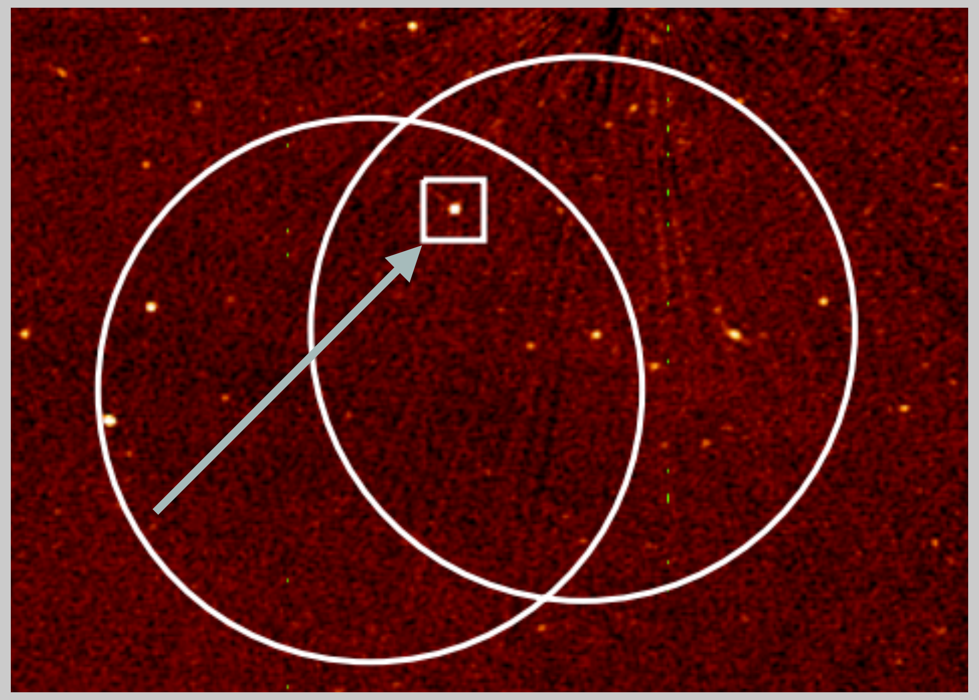


Figure 3: The host galaxy of the repeating FRB 121102 was found to be a low metallicity, star-forming dwarf galaxy, similar to the hosts of SLSNe and LGRBs. (Bassa et al. 2017)

Figure 4: The precise localization of FRB 121102 also revealed the presence of a compact radio source, which has been argued as evidence for a magnetar progenitor. (Chatterjee et al. 2017)



Fast radio bursts are bright bursts of radio emission lasting only fractions of a second and arising from extragalactic distances. Traditionally, the large localization regions of FRBs prevented unique host associations, inhibiting our understanding of the progenitors.

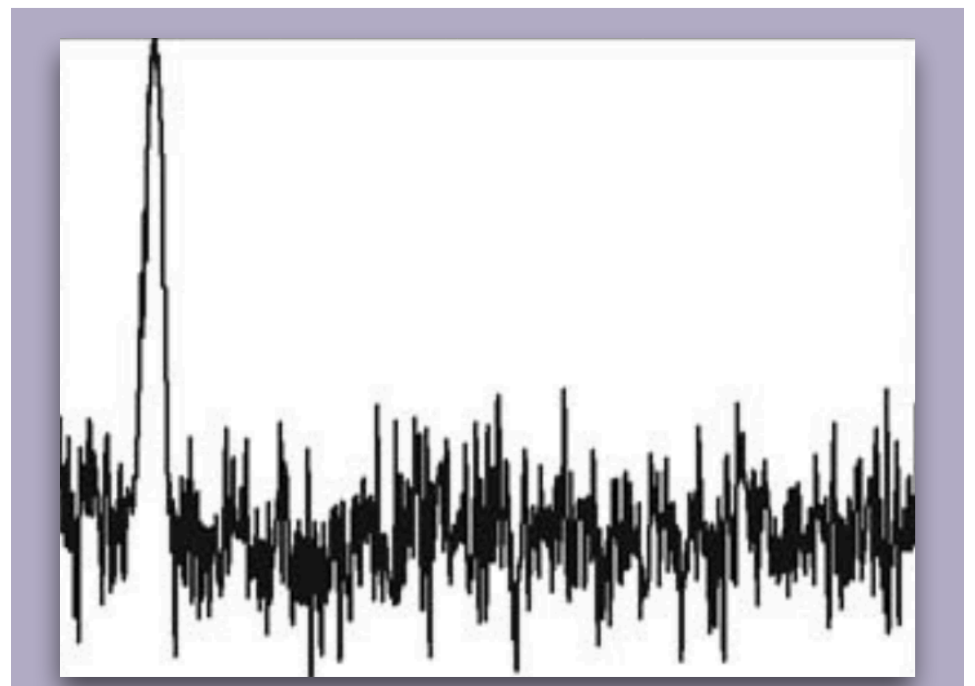


Figure 5: The first discovered fast radio burst, dubbed the "Lorimer burst." Image shows intensity as a function of time.

RADIO EMISSION FROM YOUNG MAGNETARS

Motivated by these possible connections, we conducted a large radio and millimeter survey of SLSNe and LGRBs to search for radio nebulae and fast radio bursts. The discovery of radio emission from one of these sources would provide direct evidence for a magnetar origin for the first time.

The Sample:

15 SLSNe with the Very Large Array (VLA), 29 SLSNe with the Atacama Large Millimeter/submillimeter Array (ALMA), and 7 LGRBs with the VLA

Among our sample, we detected radio emission from the location of the SLSN PTF10hgi nearly 8 years post-explosion. In Eftekhari et al. 2019, we showed that the properties of the radio emission could not be explained by star formation or emission due to an **active galactic nucleus** (AGN). Instead, we found that the observations were fully consistent with a central engine origin.

Active galactic nuclei (AGN) refer to the luminous centers of some galaxies that are powered by accretion on supermassive black holes. The powerful jets that accompany AGN are typically strong radio emitters. Thus such sources are common in the radio sky. In the case of PTF10hgi, we rule out an AGN given that the inferred black hole mass would be significantly larger than is typically seen in dwarf galaxies like the host of PTF10hgi.

We find that the same model used to describe the FRB 121102 persistent radio source can explain the observed data for PTF10hgi (Figure 7). This model, which posits a nebula of ions and electrons, can accurately characterize the luminosity of PTF10hgi simply by scaling down the magnetic energy by a factor of ~20. We also find that an off-axis relativistic jet, which are theorized to accompany SLSNe, can explain the emission. In both cases, the presence of a jet or nebula point to a central engine.

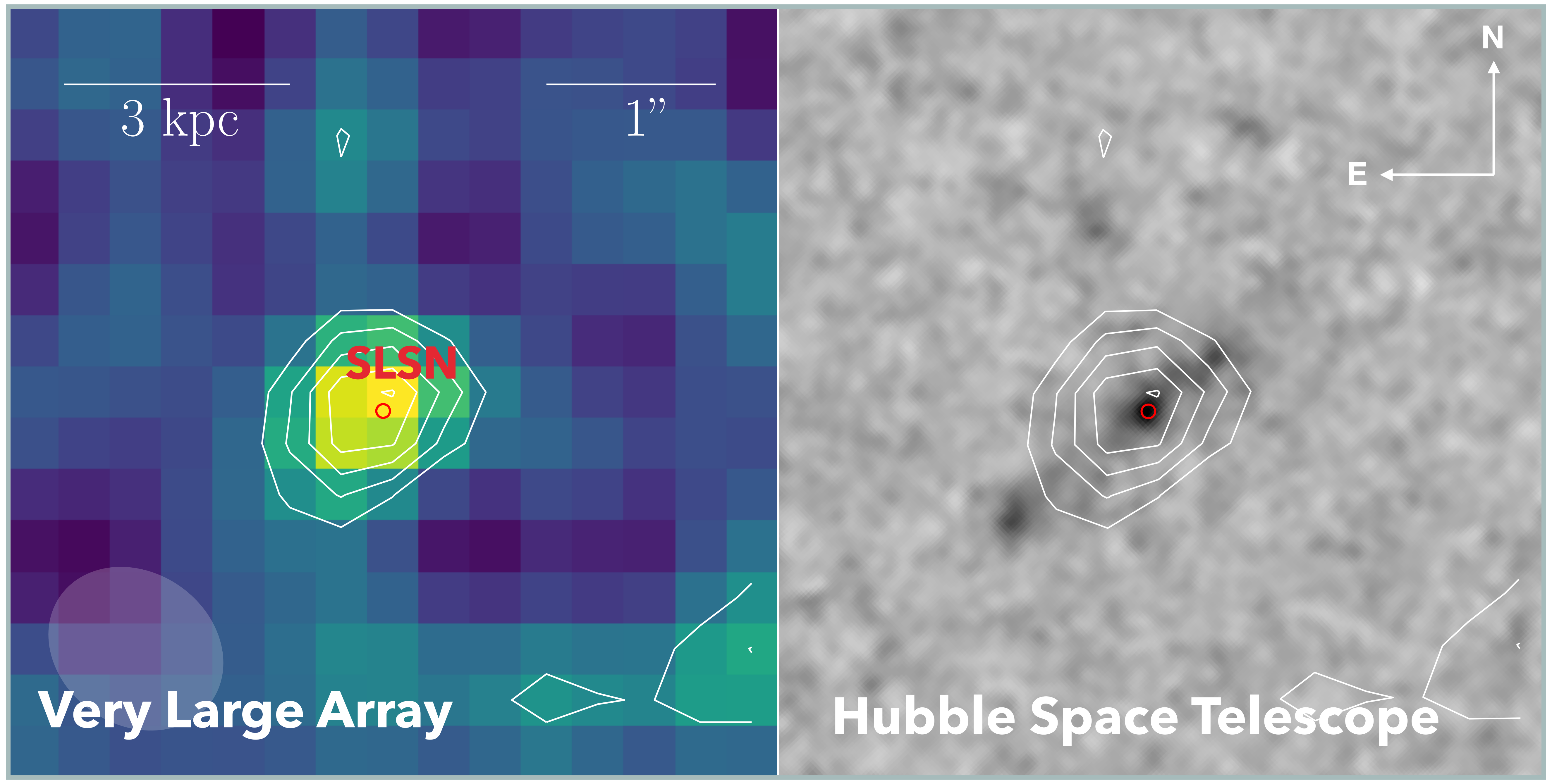


Figure 6: Radio *(left)* and optical *(right)* images of the SLSN PTF10hgi. The red circle indicates the position of the supernova.

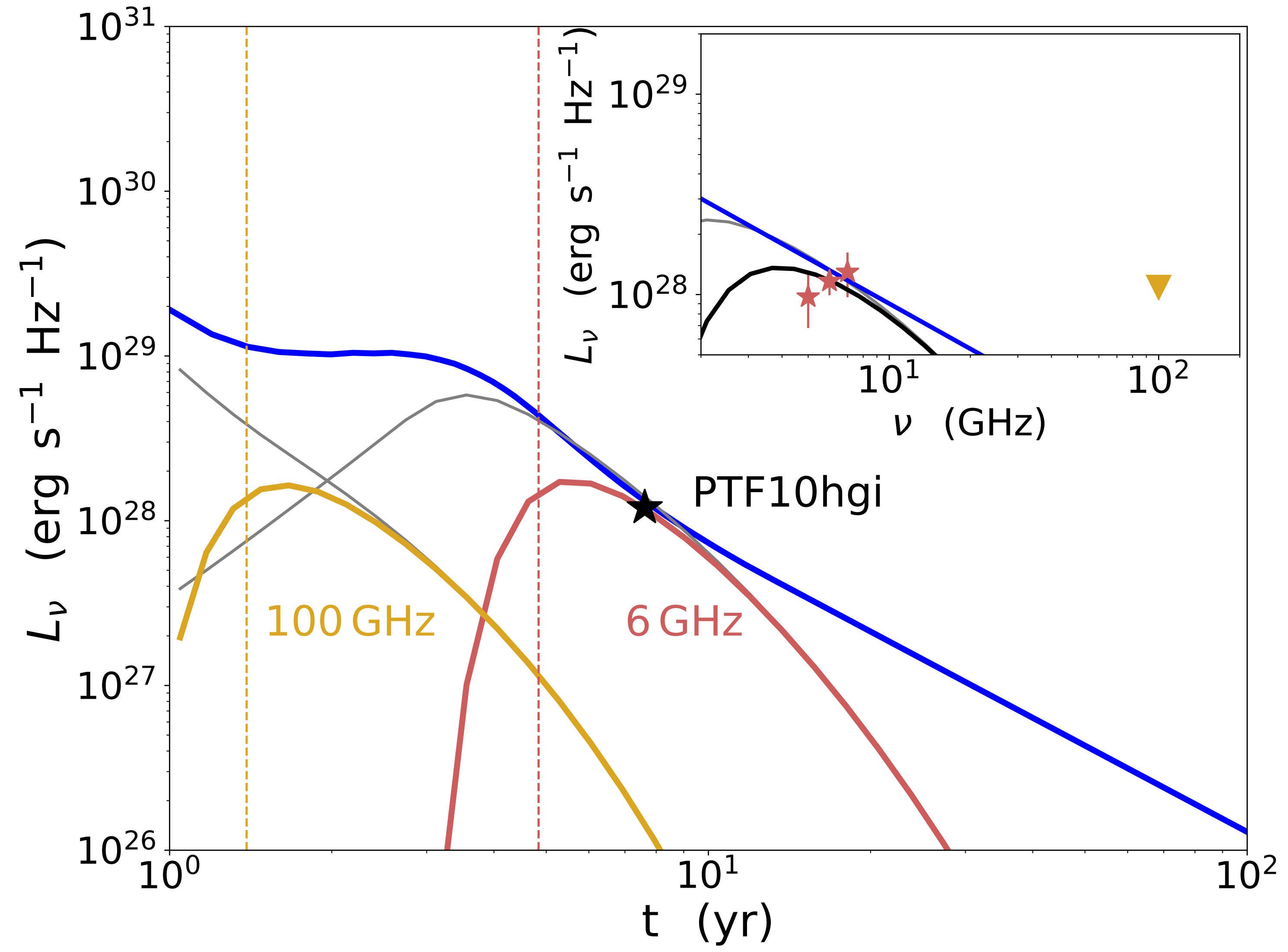
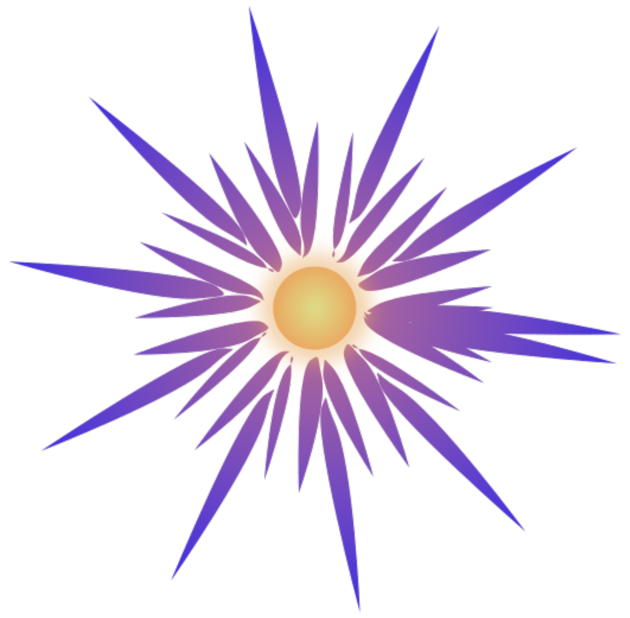


Figure 7: Radio light curve models for central engines consistent with the 6 GHz detection of PTF10hgi, including relativistic jets (blue curve) and magnetar nebulae (red and yellow curve). The models are also consistent with our non-detection at 100 GHz. The inset panel shows the SED of the source.

LATE-TIME RADIO AND MILLIMETER OBSERVATIONS OF SUPERLUMINOUS SUPERNOVAE AND

CONSTRAINING THE PRESENCE OF CENTRAL ENGINES IN OUR SAMPLE

Although we detect radio emission from the location of PTF10hgi, the remainder of sources are not detected. This begs the question whether PTF10hgi was detected merely because it is one of the closest objects in our sample, or whether the inferred engine parameters are driving the detectability of this event.



Indeed, we find that for the vast majority of our sources, the models do not predict detectable emission at the time of our observations (Figure 8). In many cases, continued monitoring on timescales of several years may lead to a detection.

Conversely, based on the models, a small handful of sources are predicted to be detectable, despite the fact that we do not detect any radio emission. This may suggest that there are details in the models that must be fine tuned for individual sources. Continued monitoring of these sources will allow us to place deep constraints on central engine models and continue to search for a connection between SLSNe, LGRBs, and magnetars.

Finally, we note that our search for FRBs from these sources has not yet led to any detections. However, based on what we know from other FRB sources, it is possible that a given source is inactive for an extended period of time. Thus continued observations to search for FRBs directly from these sources are needed! Such a connection would immediately implicate magnetars as the progenitors of SLSNe and LGRBs and confirm a connection with FRBs.

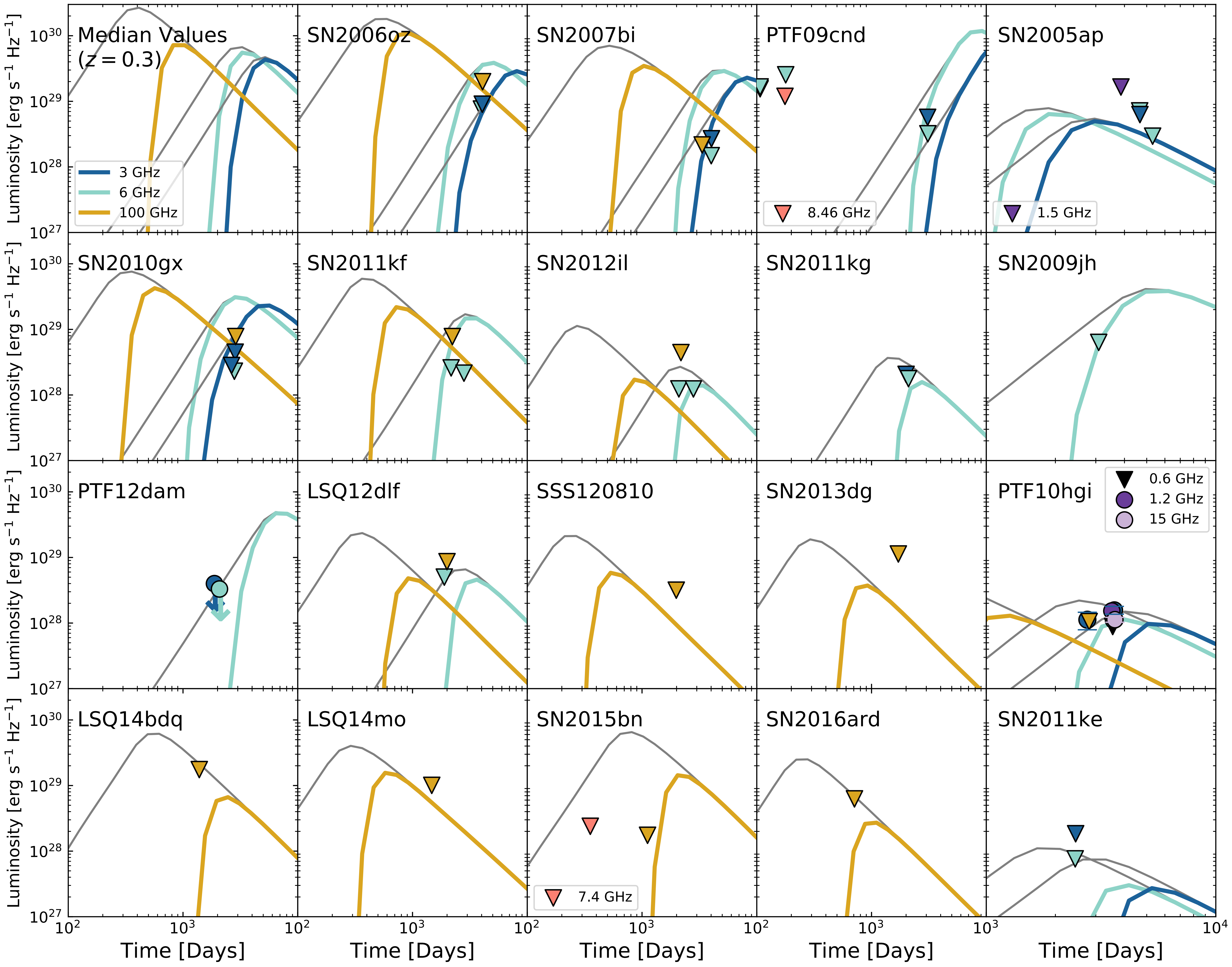


Figure 8: Magnetar nebula light curves at 3, 6, and 100 GHz using the prescription from Omand et al. 2018 for a number of our sources compared to the 3-sigma upper limits that we obtain for each source.

Citations: Bassa et al., 2017, ApJ, 843, L8; Chatterjee et al., 2017, Nature, 541, 58; Eftekhari et al., 2019, ApJL, 876, L10; Margalit et al. 2018, ApJ, 868, L4; Omand et al. 2018, MNRAS, 474, 573;

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