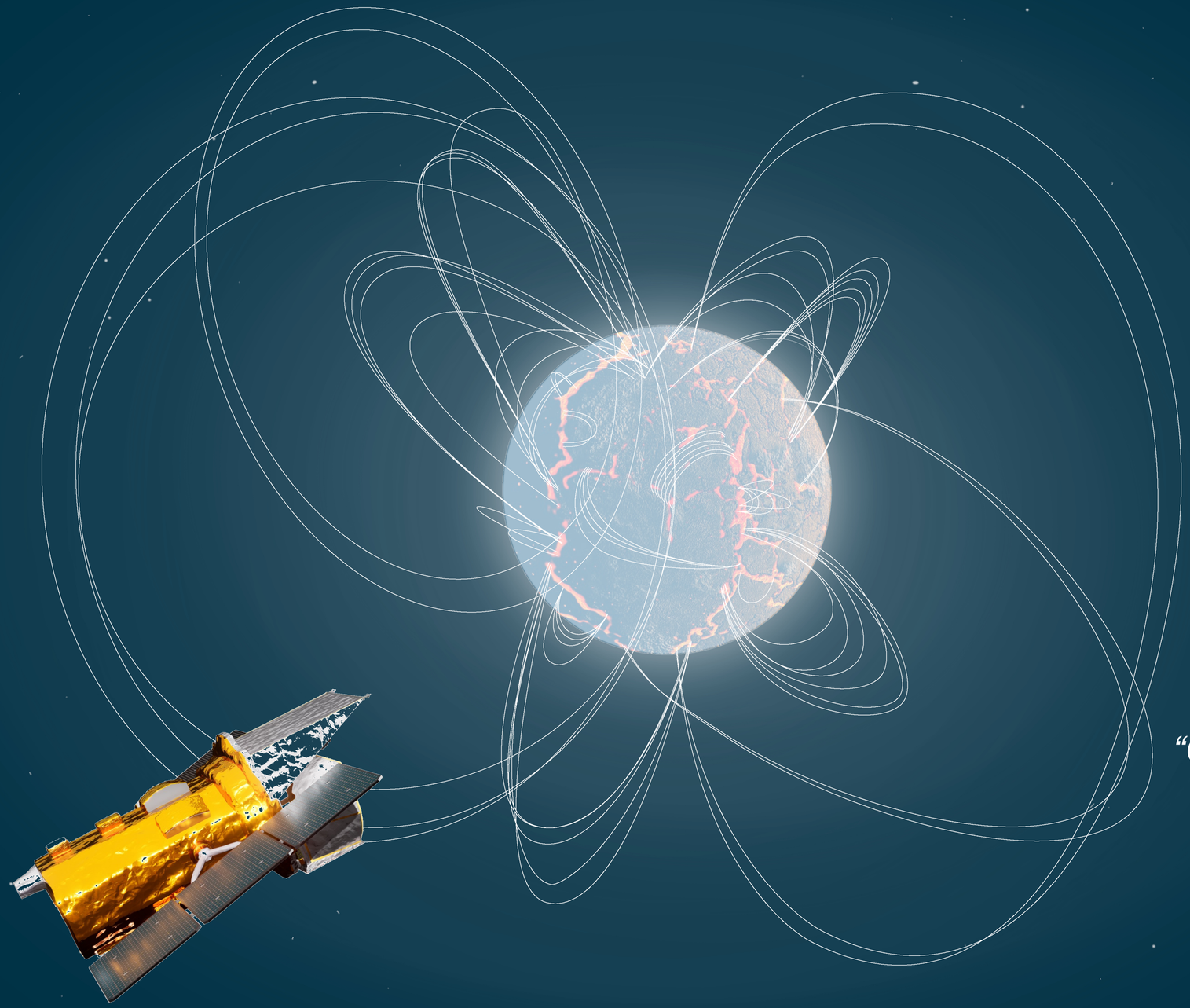


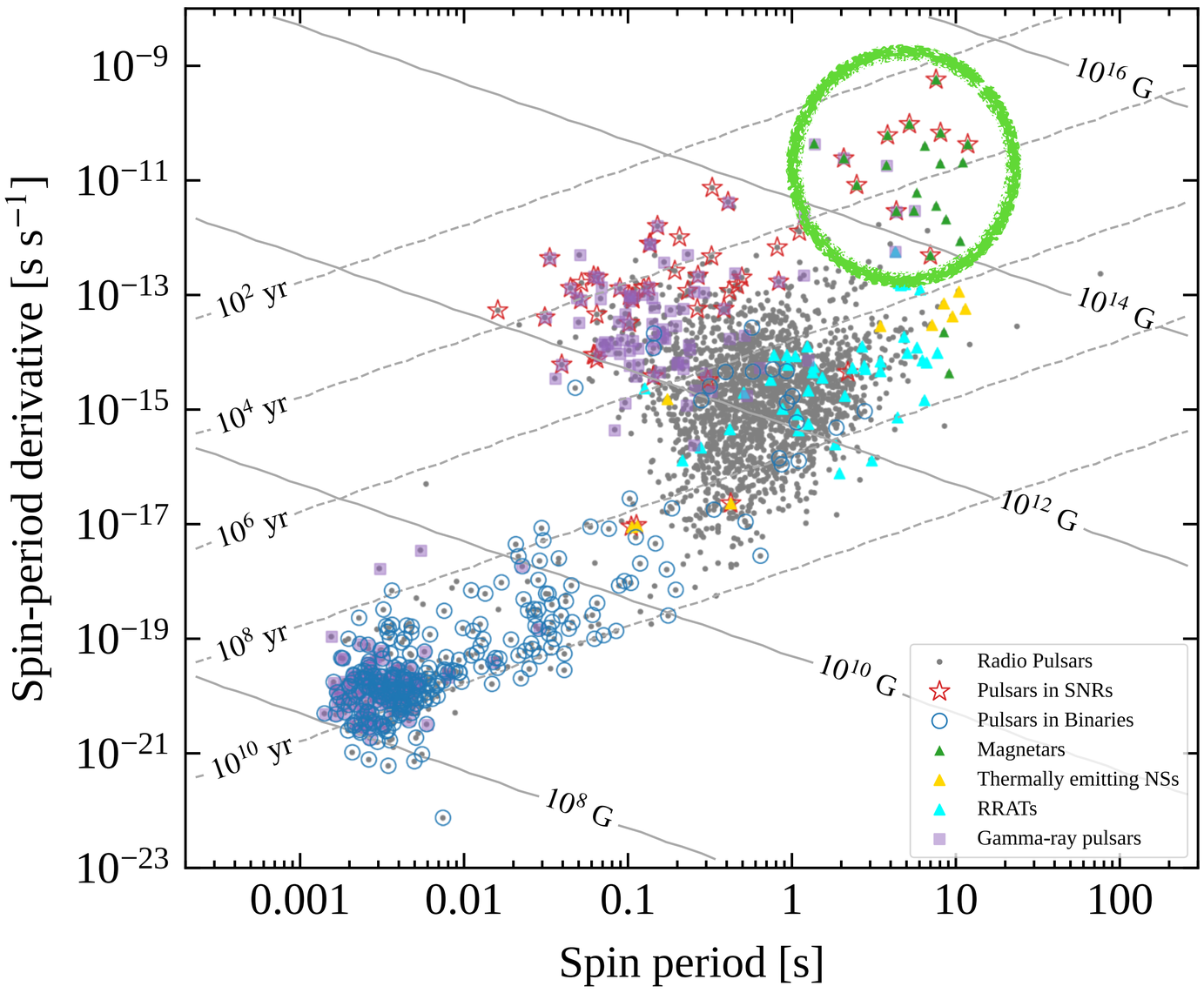
Systematic study of magnetar outbursts

Francesco Coti Zelati

CSIC Institute of Space Sciences — EXCELENCIA MARÍA DE MAEZTU

“Celebrating 20 years of Swift Discoveries”
Florence, March 26th 2025

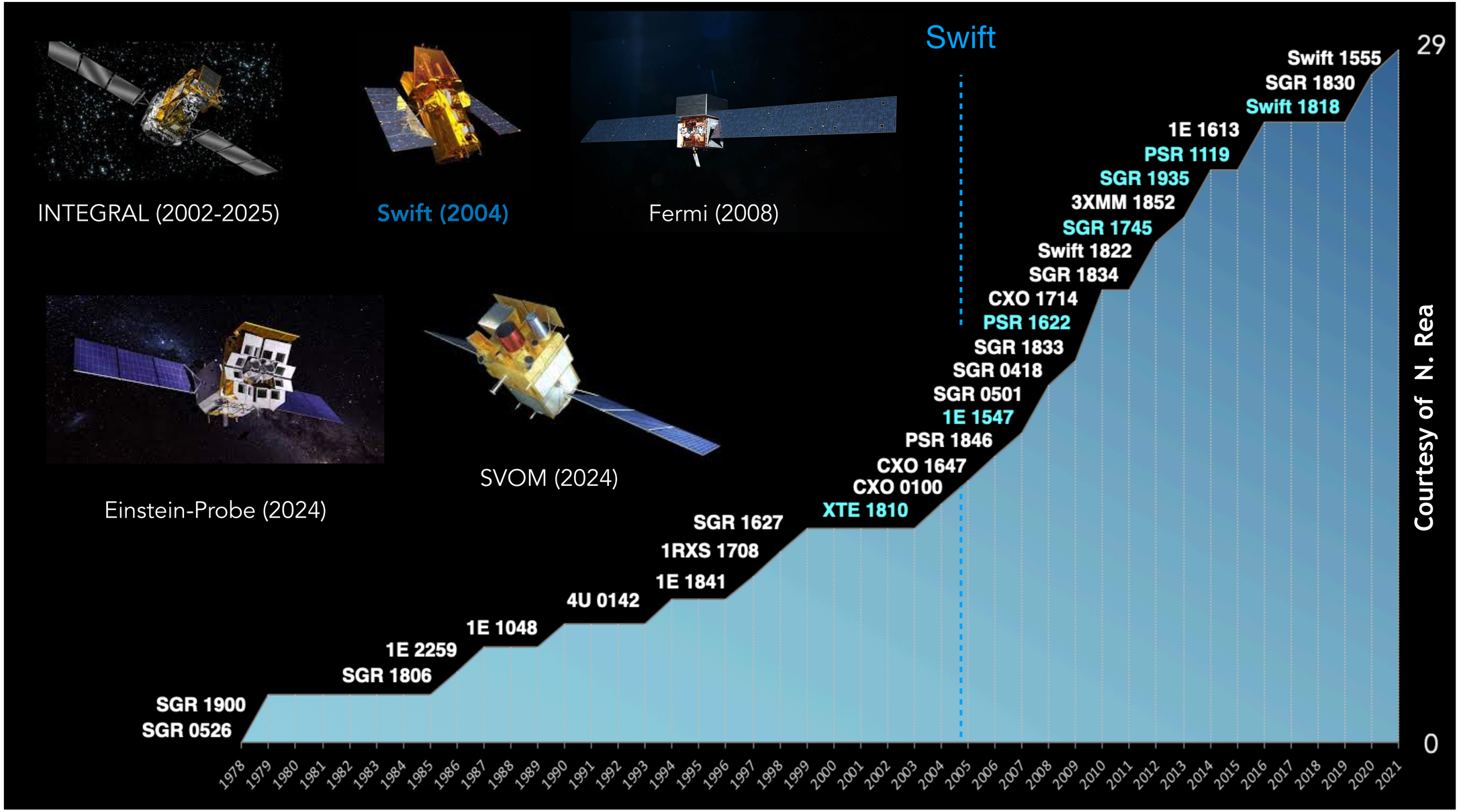
Magnetars



- ~30 X-ray pulsars (Lx ~ 10^{31} - 10^{36} erg s^{-1})
- Broadband X-ray emission (0.5-200 keV); thermal + non-thermal spectrum
- P ~ 0.3 - 12 s
- B_p~10^{13} - 10^{15} Gauss
- Bursting activity in X-ray/gamma-ray bands (0.01 - 10^2 s; L_x ~10^{38} - 10^{46} erg s^{-1}) and outbursts
- Highly polarized X-ray emission
- Pulsed/bursting radio emission

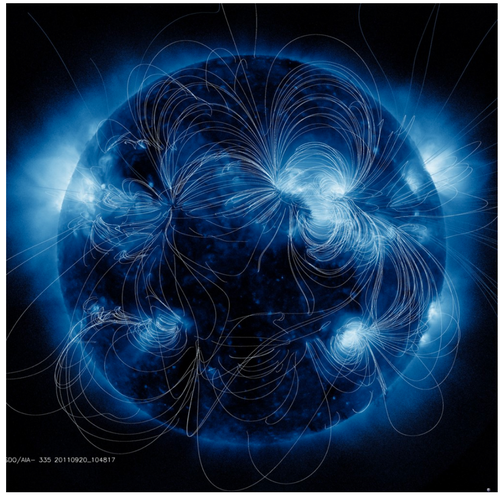
Turolla et al. 2015; Kaspi & Beloborodov 2017; Esposito et al. 2021; Taverna & Turolla 2024

Discovery rate



Outburst activity: mechanisms

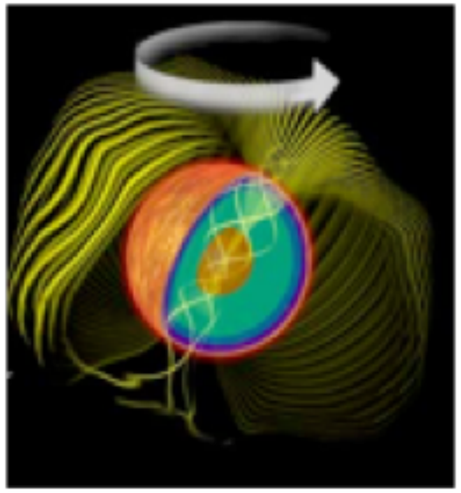
Internal source of heat



Plastic flows in the crust convert magnetic energy into heat

Heat conducted up and radiated

External source of heat



Crustal displacements twist up the external B-field.

Returning currents hit the surface

Both scenarios make predictions that can be tested

Nobili et al. 2008a,b; Beloborodov 2009; Pons & Rea 2012; Beloborodov & Levin 2014; Beloborodov & Li 2016; Akgün et al. 2018; Carrasco et al. 2019; De Grandis et al. 2020, 2025

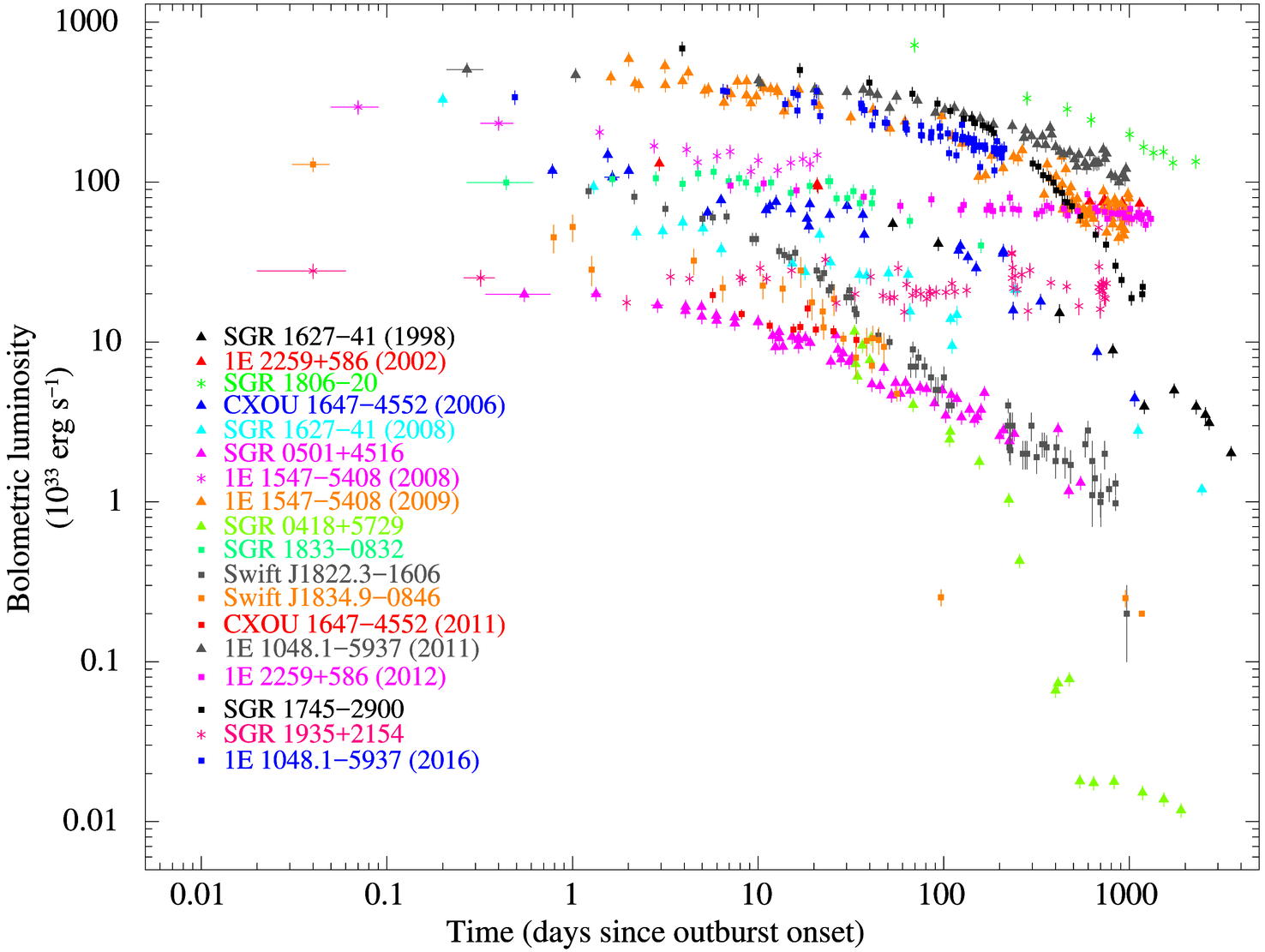
Systematic study of Magnetar outbursts

- About 1100 X-ray observations (12 Ms) between from 1998 to 2017; >1000 Swift jobs
- Spectral fitting with empirical and more physically-motivated models
- Light curve modelling and estimate of energetics and decay time scale

$$L(t) = L_q + \sum_{i=1}^{j} A_i \times \exp(-\mathrm{t}/\tau_\mathrm{i}) \qquad E = \int_0^{t_{qui}} L(t)dt$$

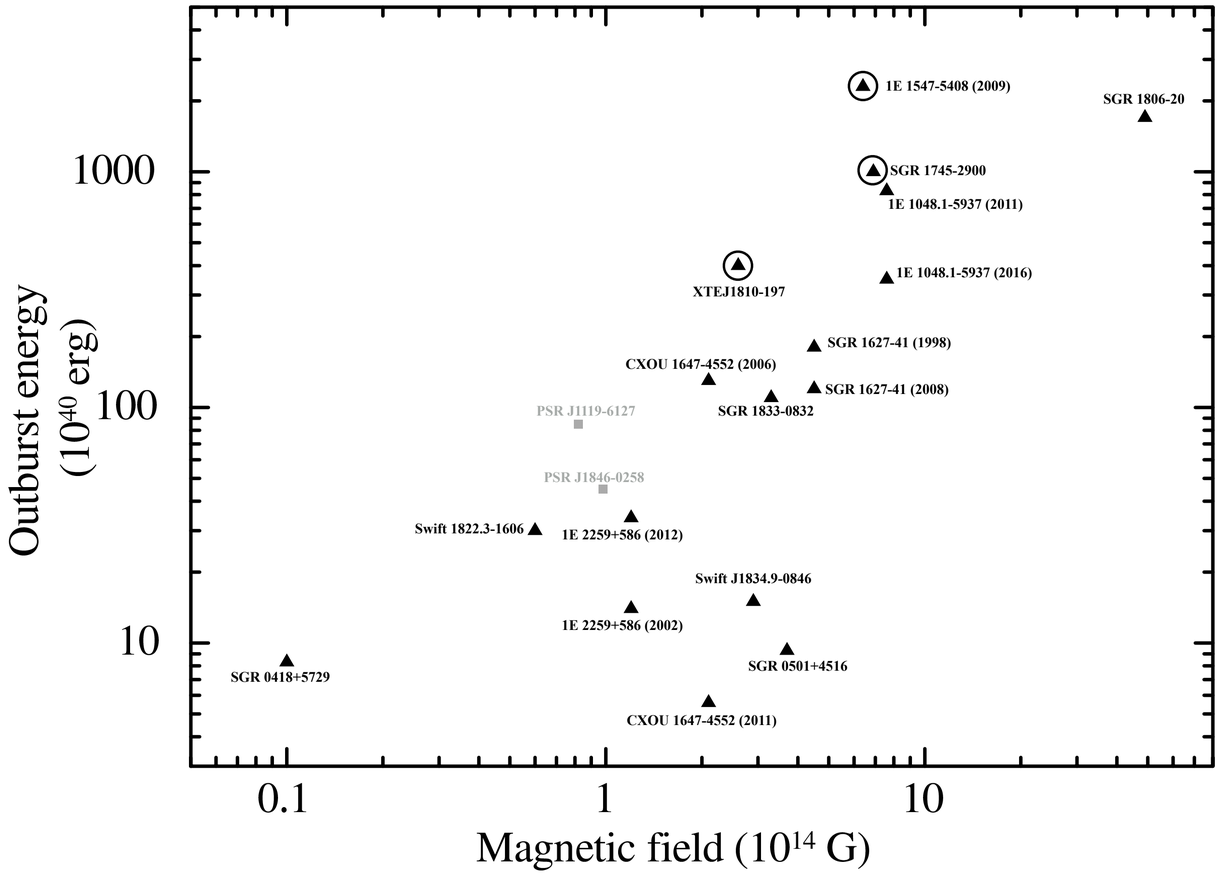
All performed in a homogeneous and consistent way for the first time

Magnetar outbursts light curves

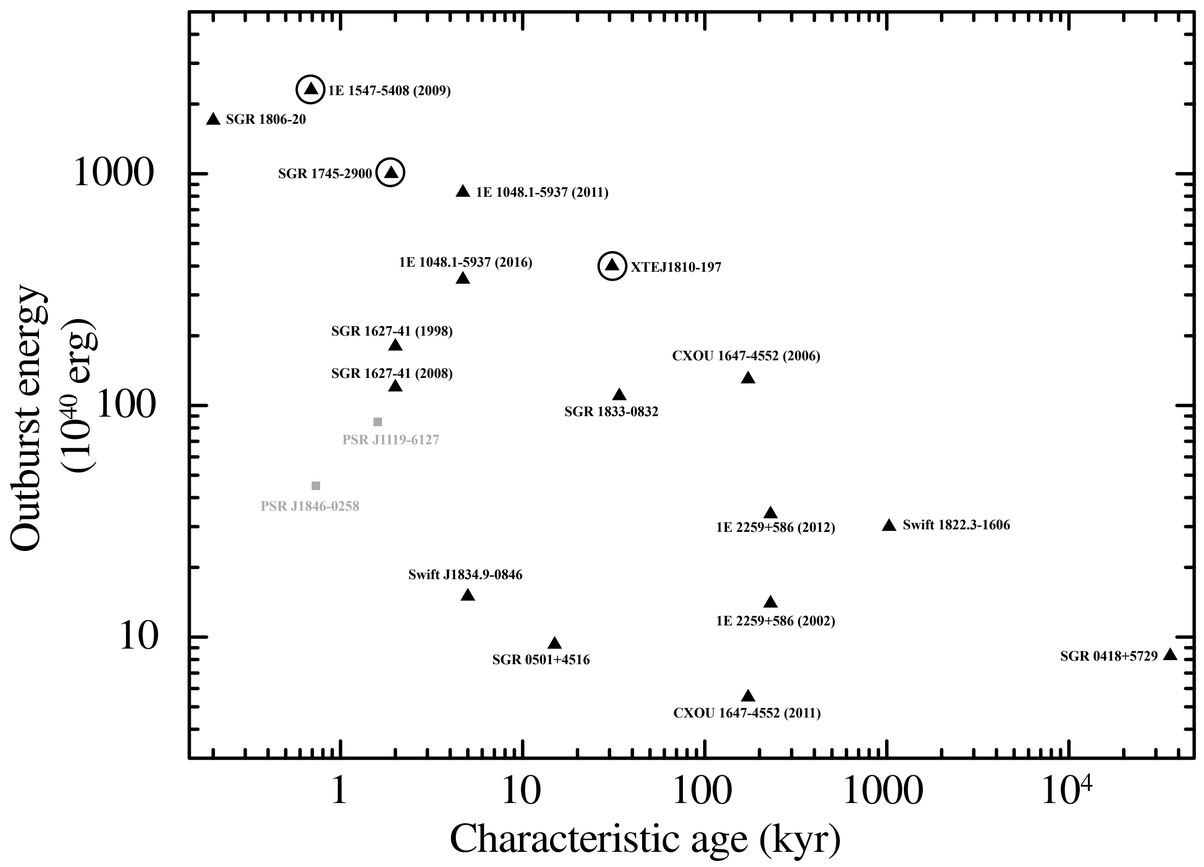


Correlations and trends

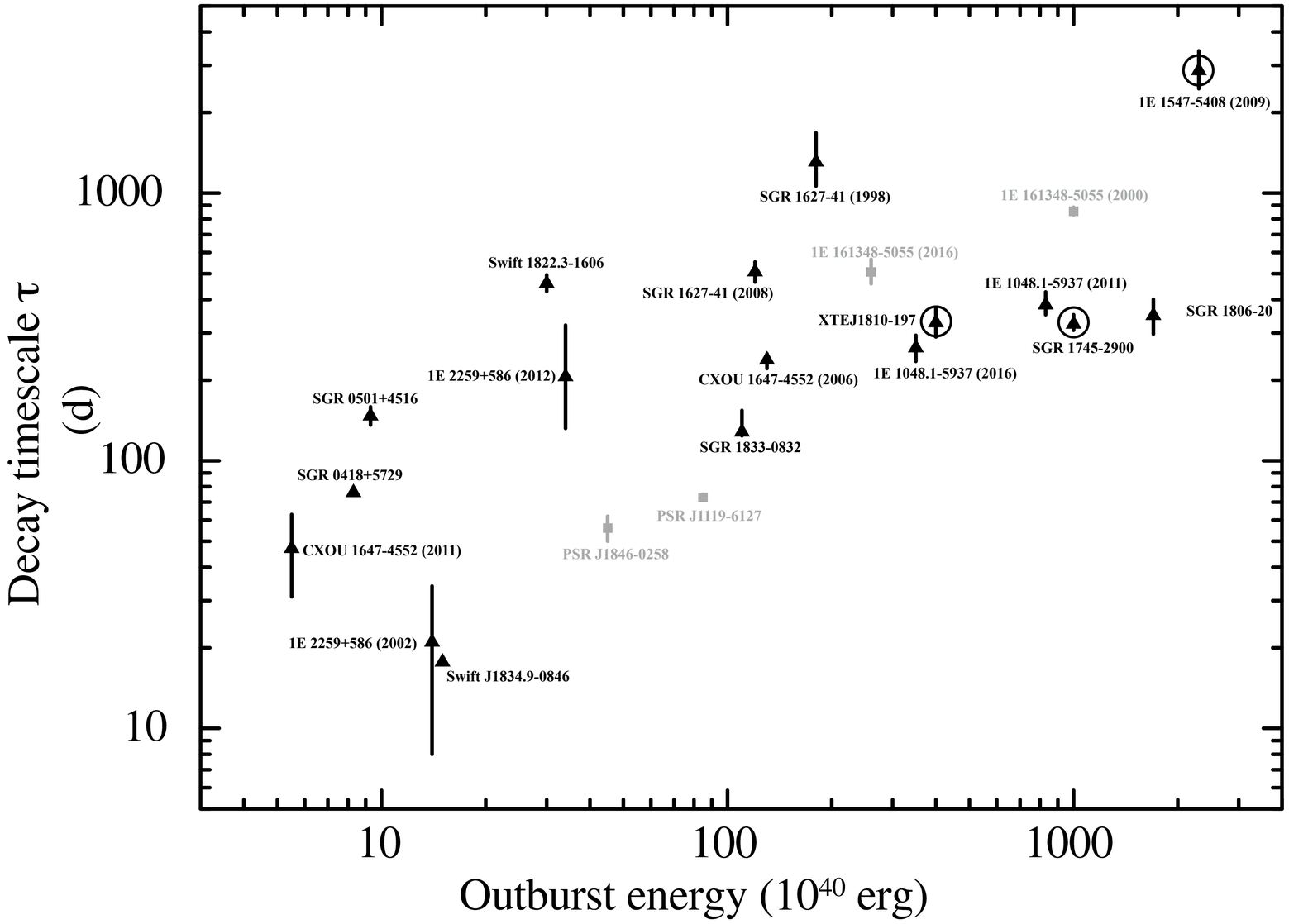
Magnetar outbursts are ultimately powered by the dissipation of the magnetic field



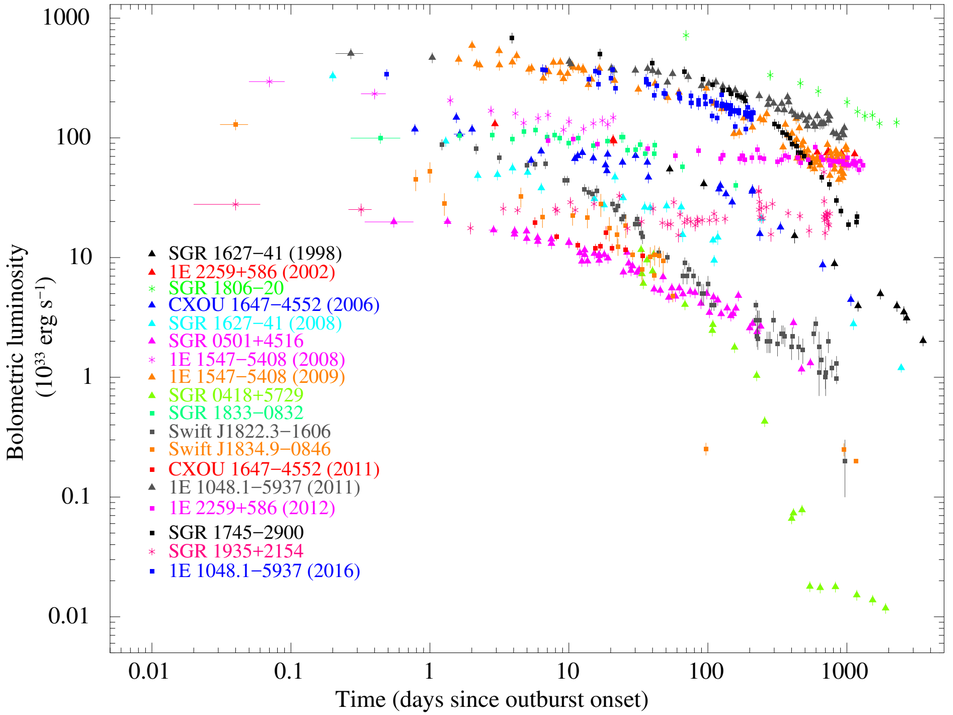
Younger magnetars undergo more energetic outbursts



Correlations and trends

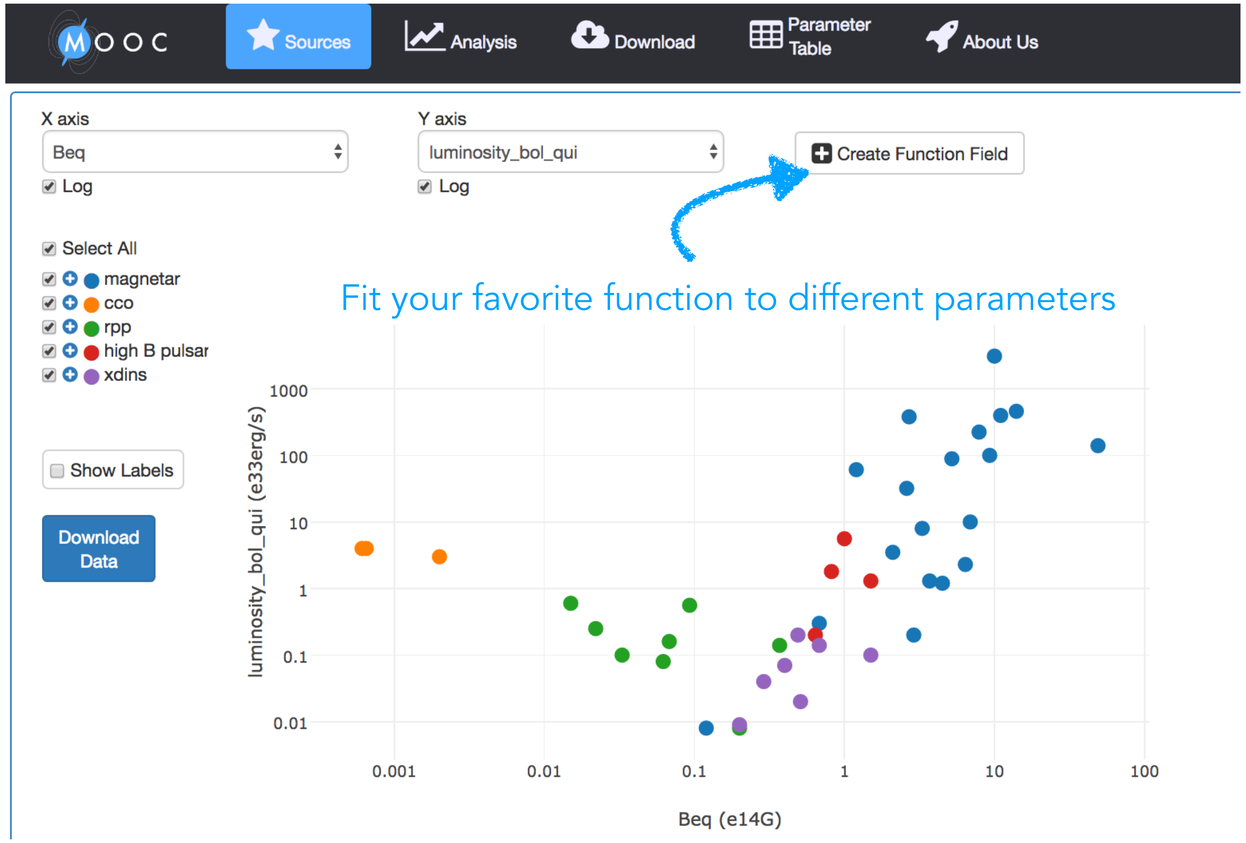


Similar decay pattern for all magnetar outbursts

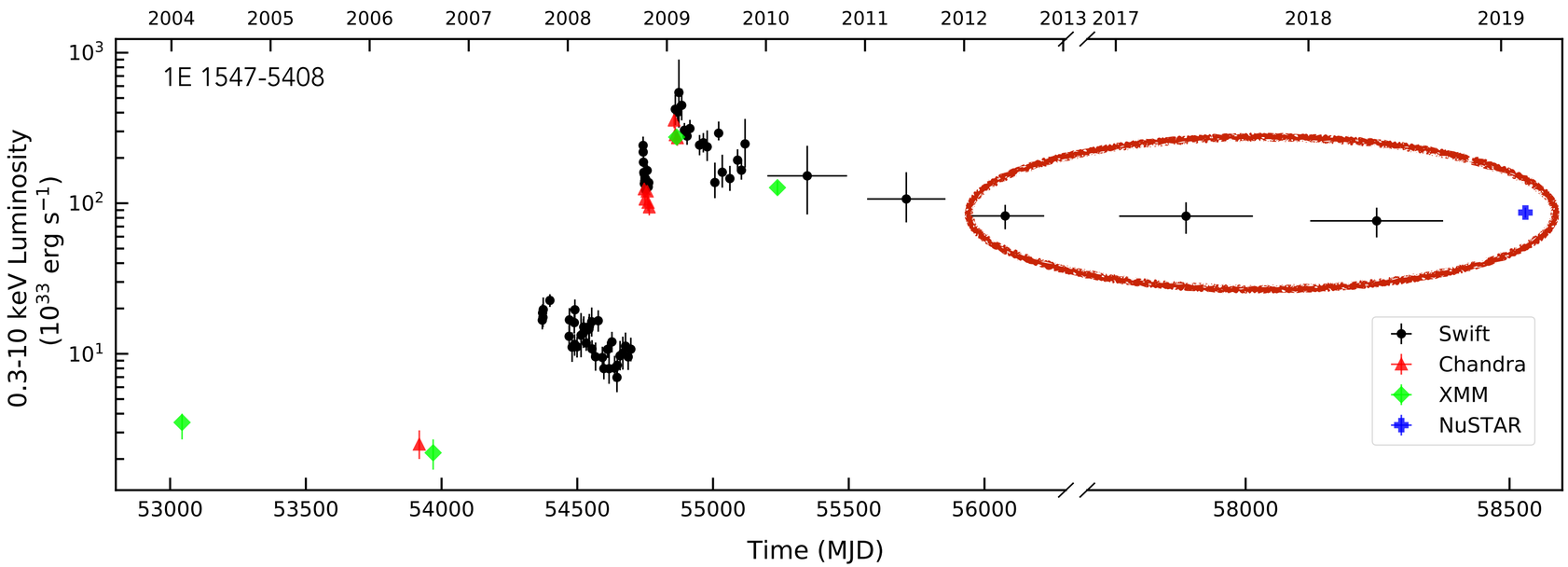


Magnetar Outbursts Online Catalogue

Coti Zelati et al. 2018
Magnetar Outburst Online Catalog
http://magnetars.ice.csic.es/



Updating the catalogue: an inexhaustible magnetar



A much brighter persistent state compared to 2004-2007

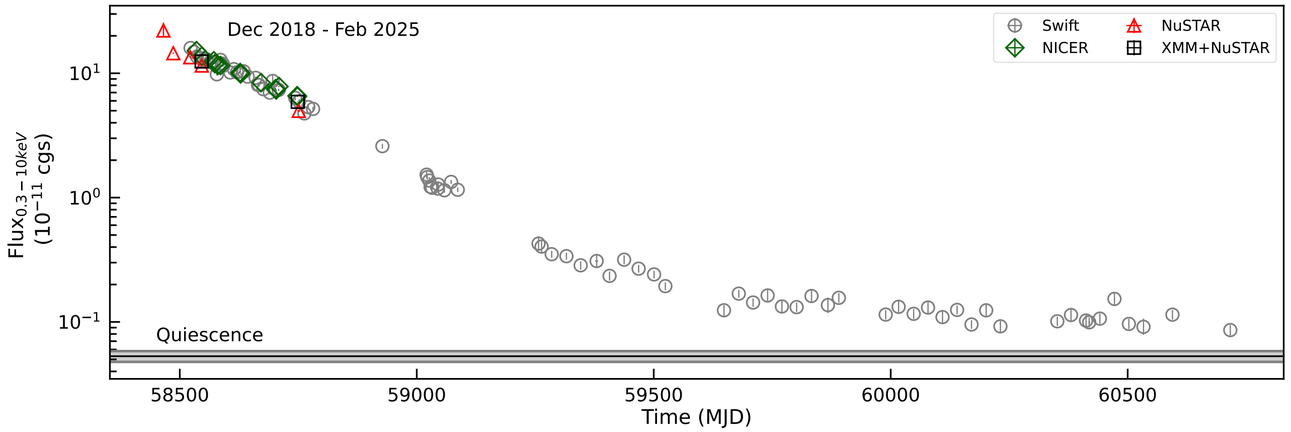
Hard X-ray emission still detectable 10 years after the 2009 outburst

Magnetar thermal emission can be largely driven by dissipation of magnetospheric currents.

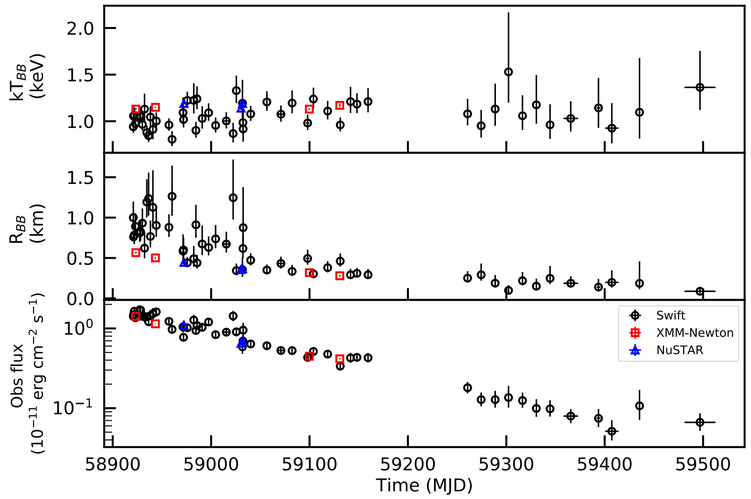
FCZ et al. 2020

Updating the catalogue: recent magnetar outbursts

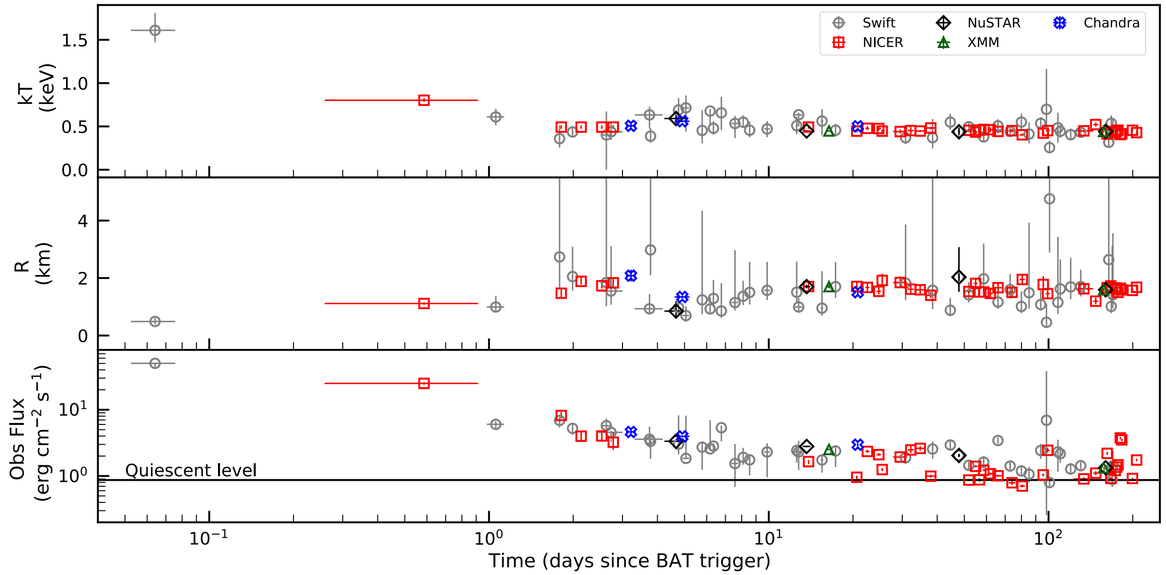
XTE J1810-197 (Borghese et al. to be subm.)



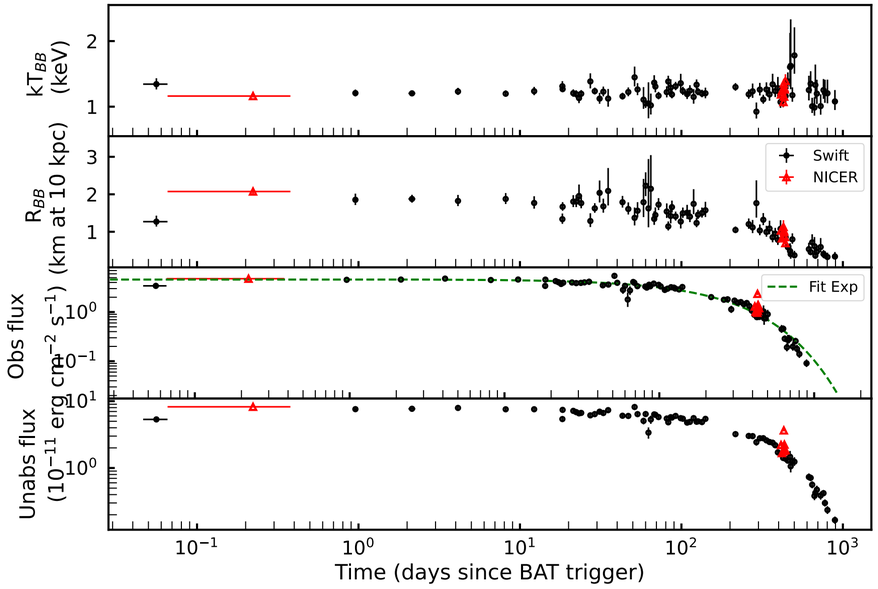
Swift J1818.0-1607, Mar 2020- Oct 2021 (Ibrahim … FCZ et al. 2022)



SGR 1935+2154, Apr-Nov 2020 (Borghese et al. 2020)



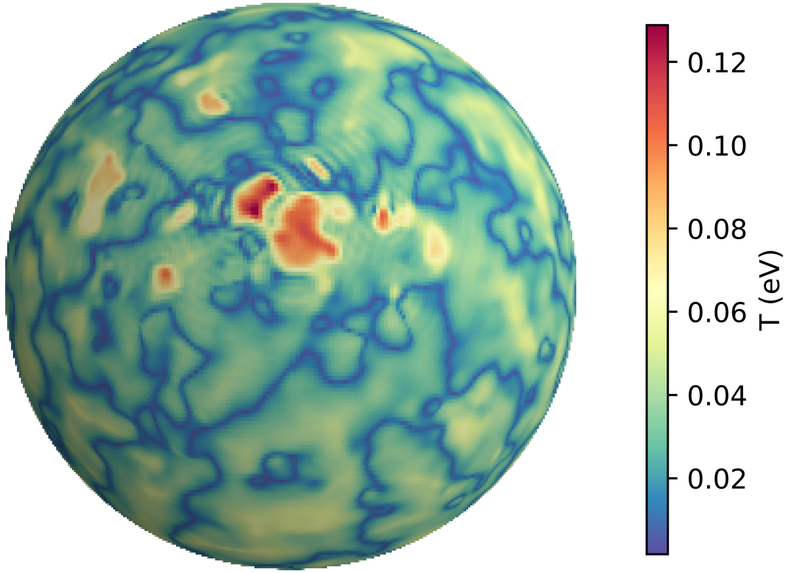
Swift J1555.2-5402, Jun 2021-Oct 2023 (Borghese, FCZ + in prep)

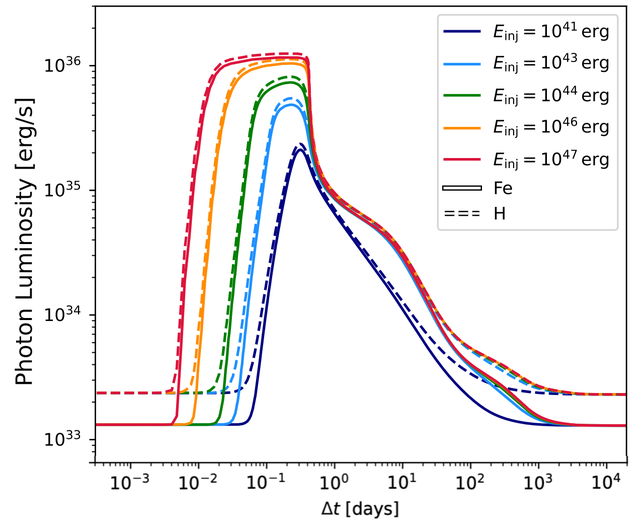


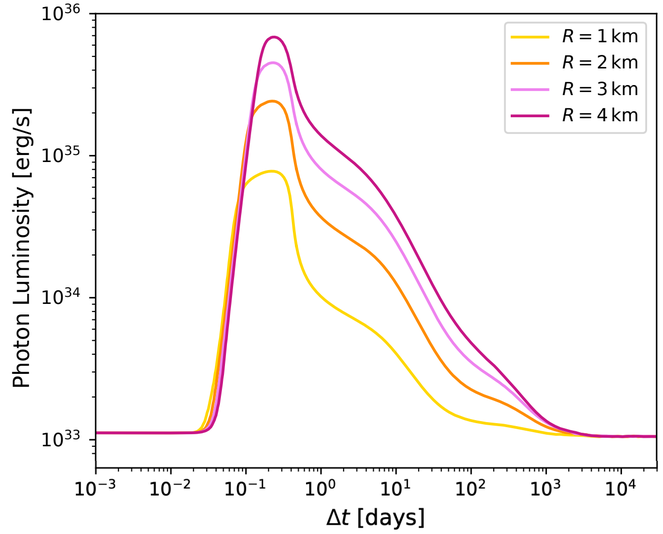
Modeling outburst light curves: cooling simulations

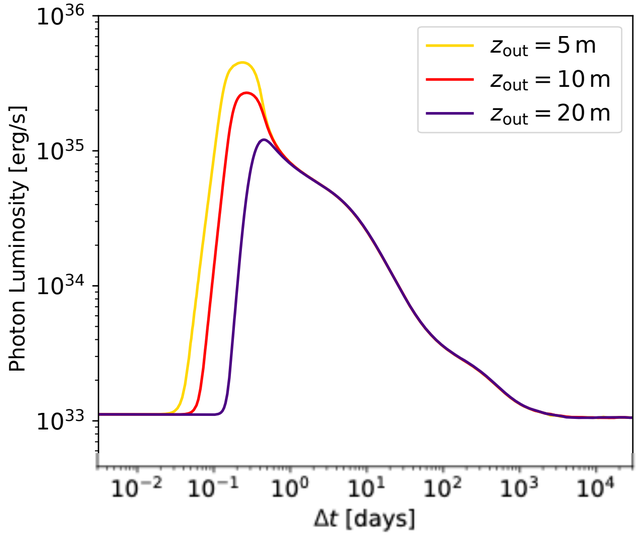
Simulations of localised heat deposition in the crust

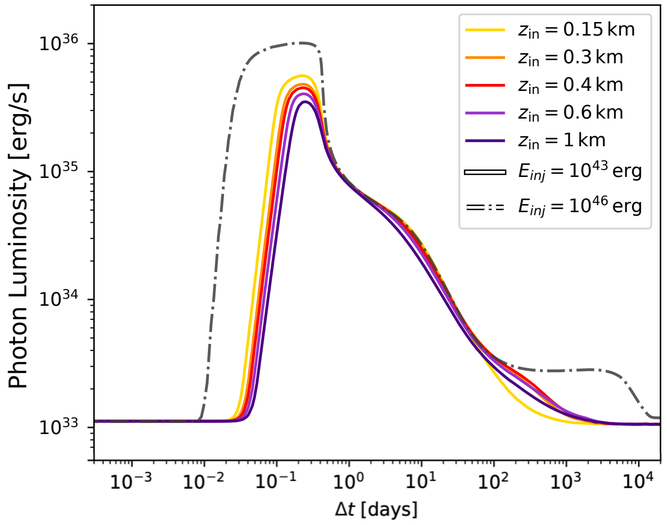
The cooling of a small hotspot in the outer crust can account for the observed luminosity evolution in terms of peak luminosity and timescales





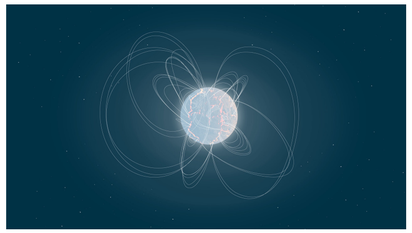


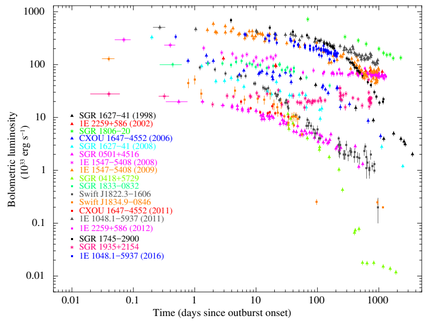


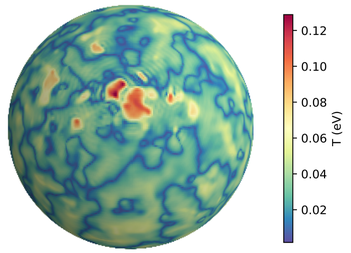


De Grandis … FCZ et al. subm.

Conclusions and future prospects

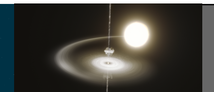




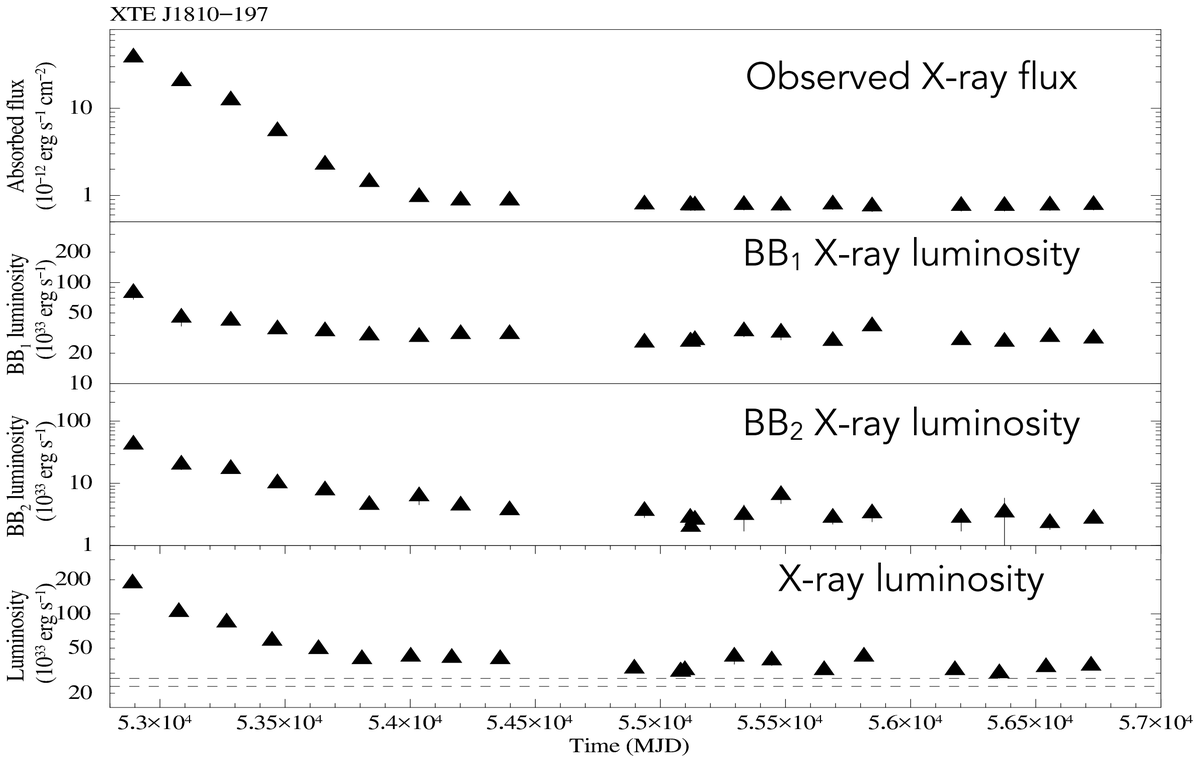


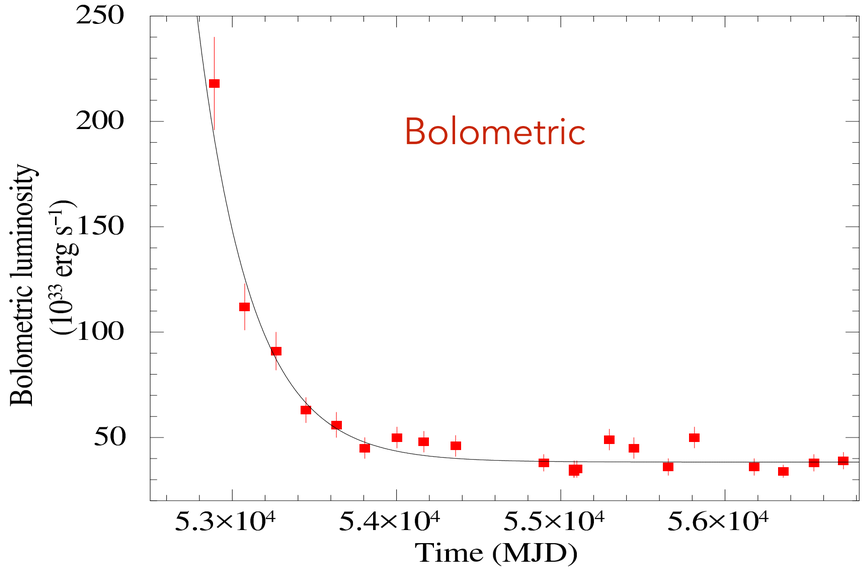
- Dedicated observing campaigns of magnetar outbursts are crucial to understand emission mechanisms and discover peculiar sources
- Online catalogue presenting over 1100 X-ray observations and offering a powerful tool to fit models to data
- Cooling simulations of localized crustal heating successfully reproduce the observed luminosity evolution.
- A new version of the catalogue soon to be realized — stay tuned!

Backup slides



Systematic study of magnetar outbursts



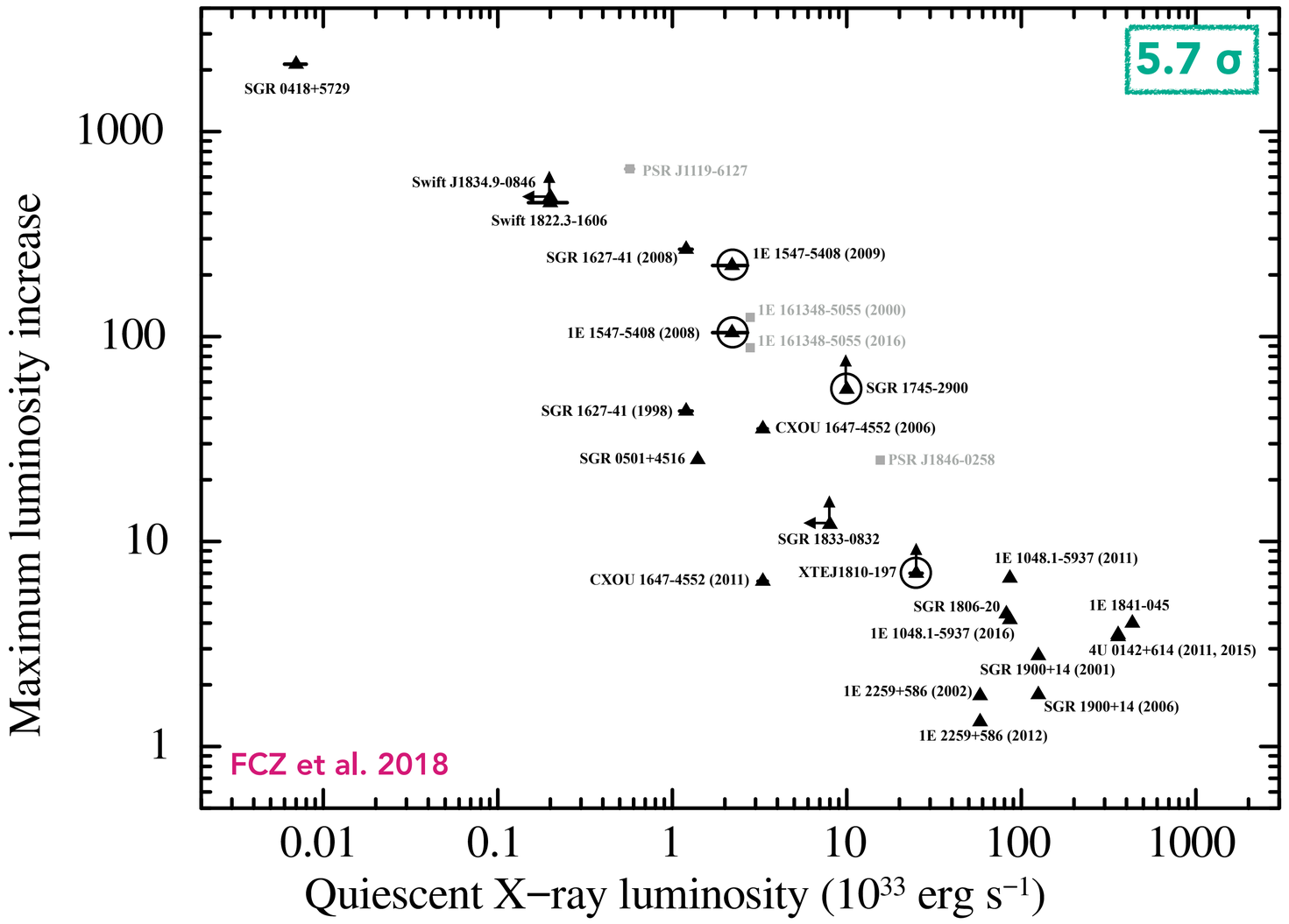


Estimate of the outburst
decay-timescale and energetics

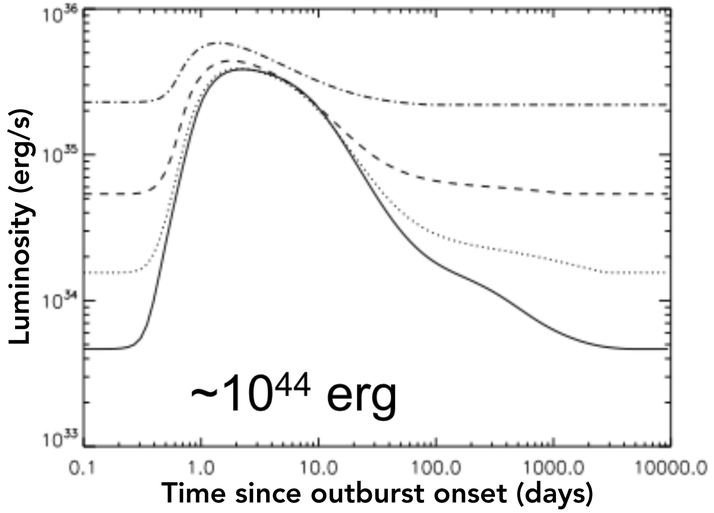
$$L(t) = L_q + \sum_{i=1}^{j} A_i \times \exp(-\mathrm{t}/\tau_\mathrm{i})$$

$$E = \int_0^{t_{qui}} L(t)dt$$

Systematic study of Magnetar outbursts

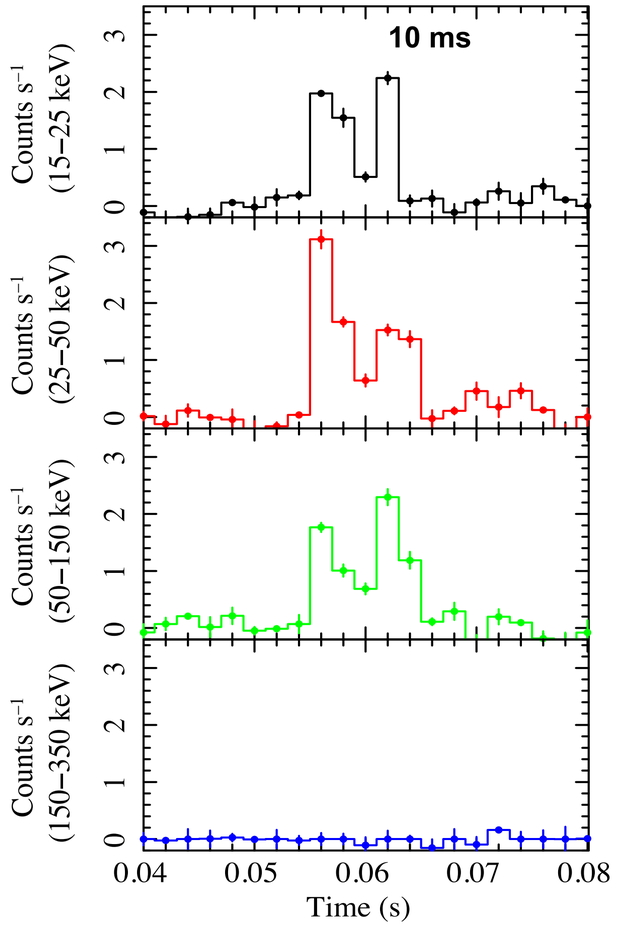


Large flux enhancements are observable only in faint quiescent magnetars

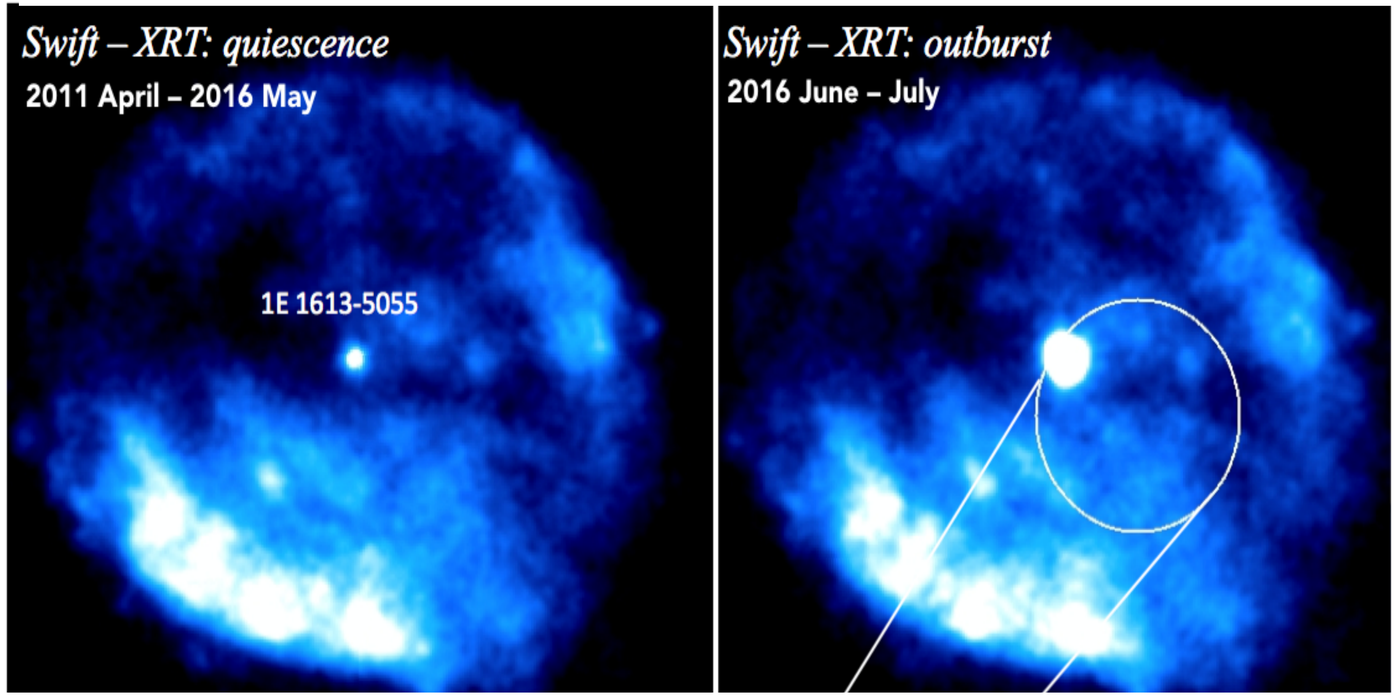


Magnetar-like activity from a central compact object

A magnetar-like burst and outburst (2016 June)



$L_X = 2 \times 10^{39}$ erg s^{-1}



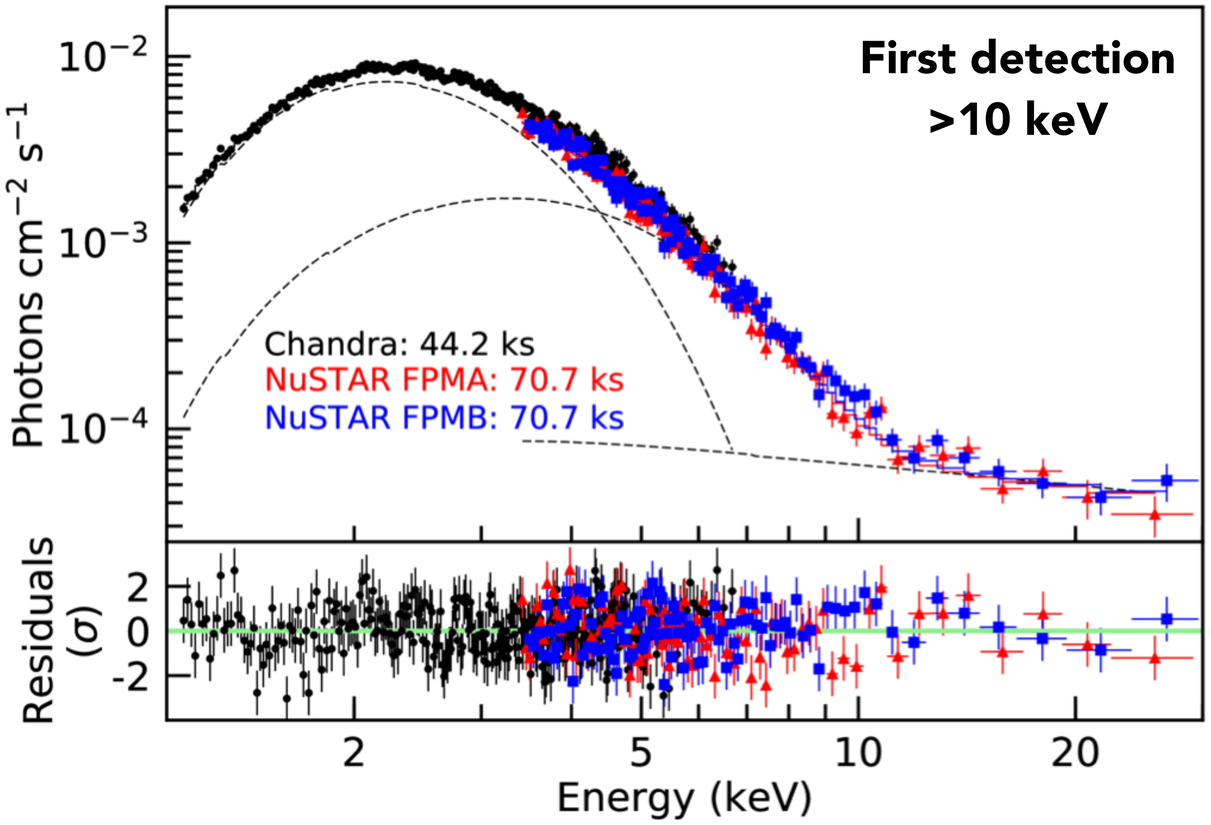
$F_X \sim 2 \times 10^{-12}$ erg cm^{-2} s^{-1}

$F_X \sim 1 \times 10^{-10}$ erg cm^{-2} s^{-1}

Rea et al. 2016 (including FCZ as corresponding author), ApJL

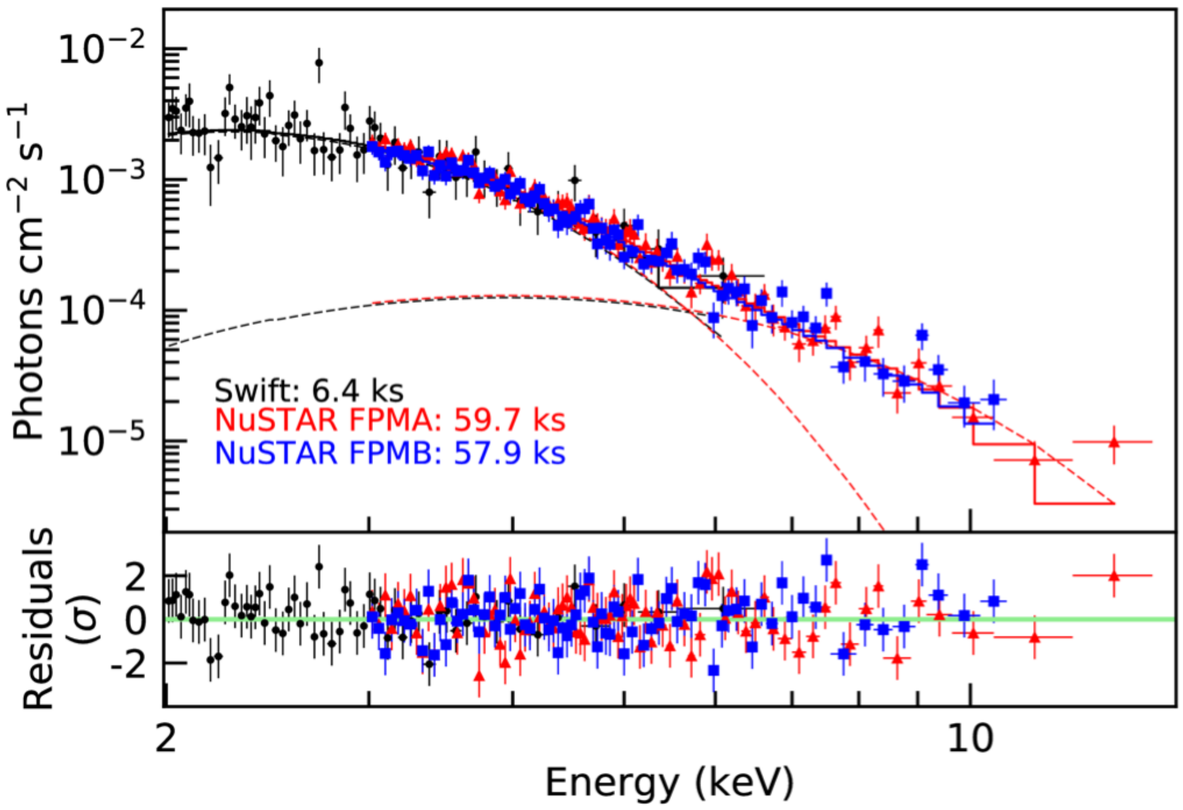
Magnetar-like activity from a central compact object

A magnetar-like spectrum at the outburst peak



Rea,..,FCZ et al. (2016)

Softening along the decay (about 1 year later)



Borghese, FCZ et al. (2018)

Modeling outburst light curves: cooling simulations