Comptonized Relativistic Winds in Magnetar Giant Flares

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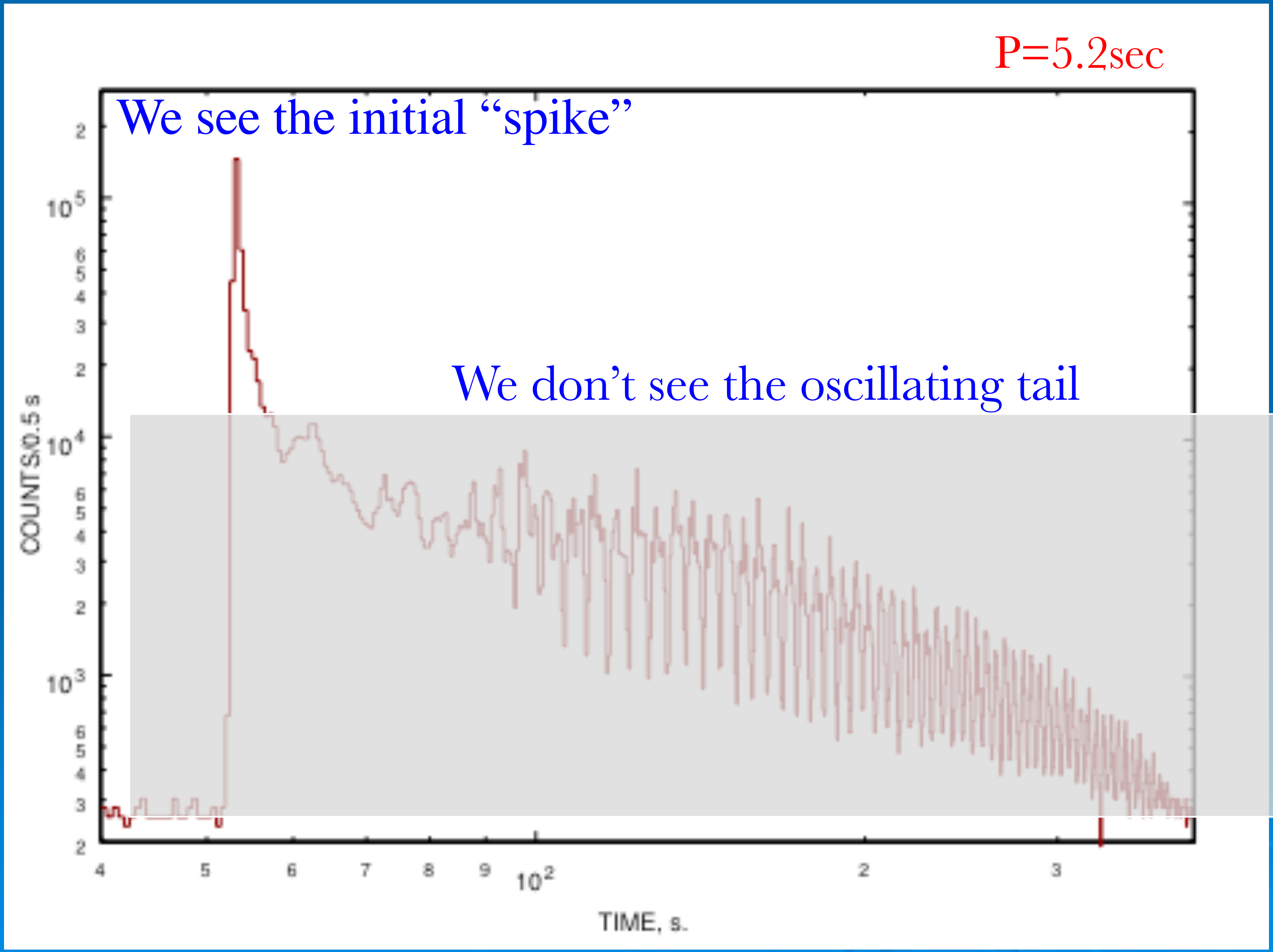
Extragalactic Magnetar Giant Flare (MGF)



SGR 1900+14 MGF: source Kevin Hurley

GRB 200415A: *Fermi*-GBM and *Swift*-BAT

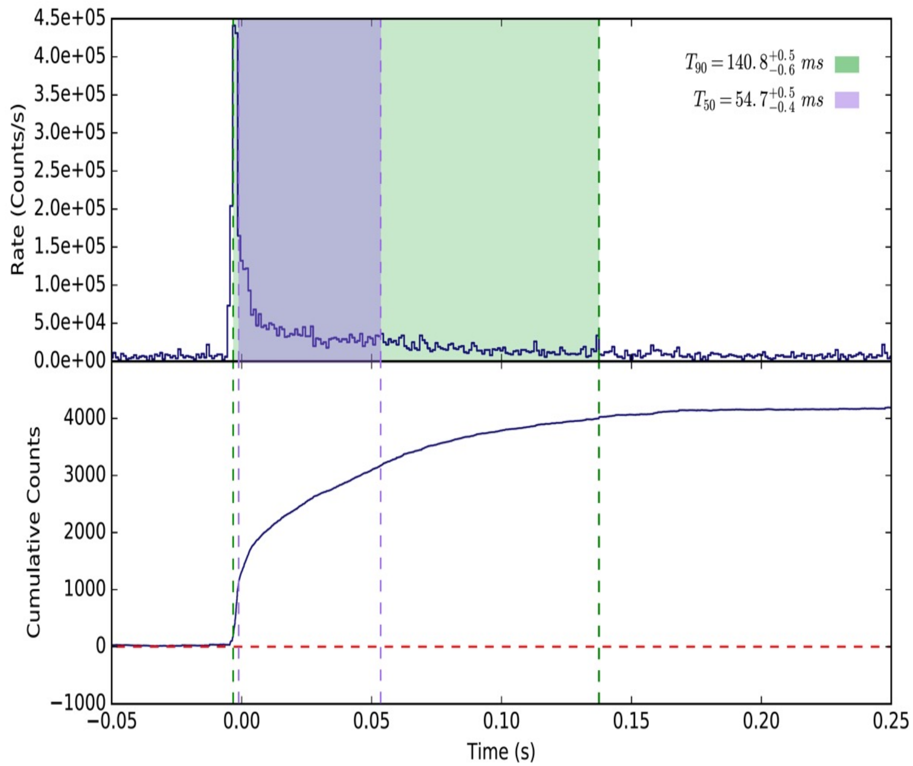
Localized to NGC 253 (Sculptor)

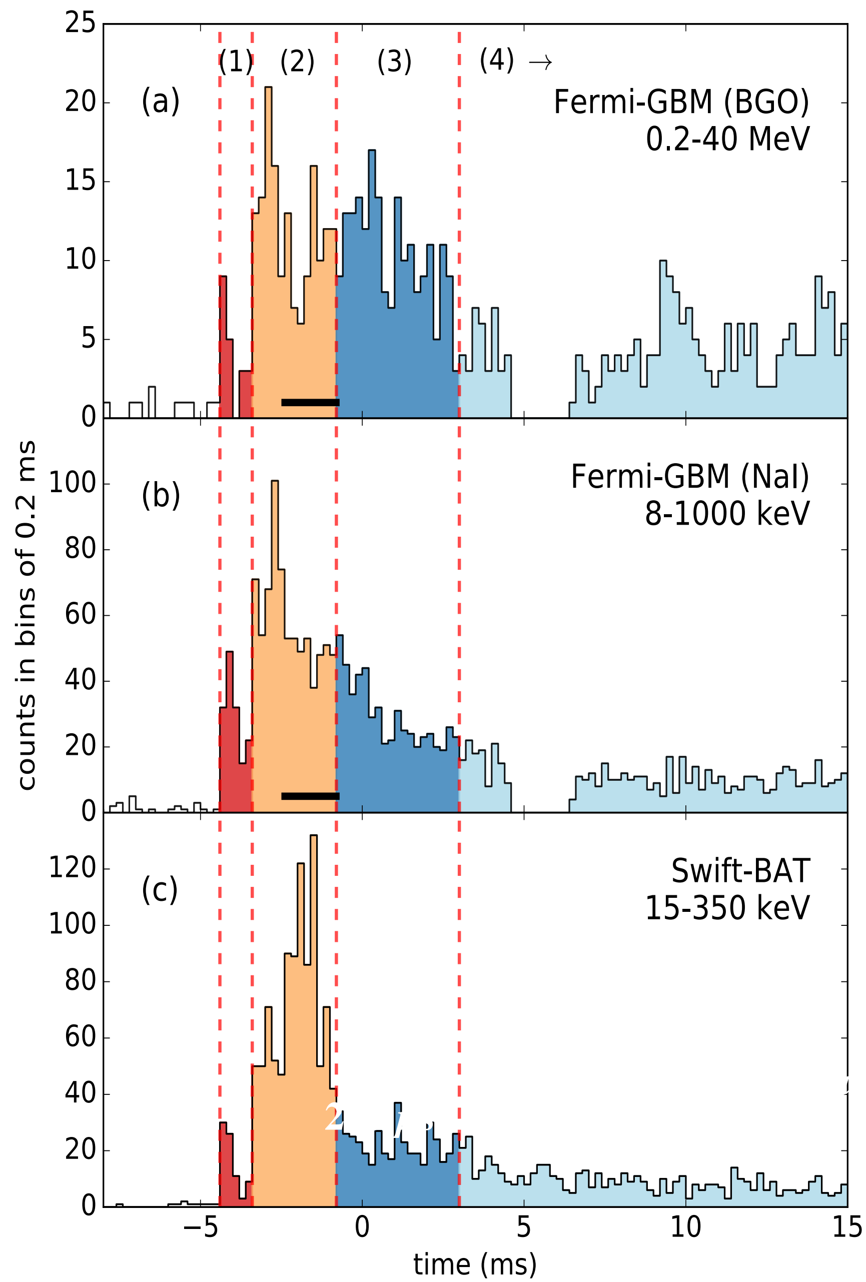
Total energy emitted: 10^{46} erg.

Total luminosity emitted: 10^{47} erg s^{-1}.

No modulated tail.

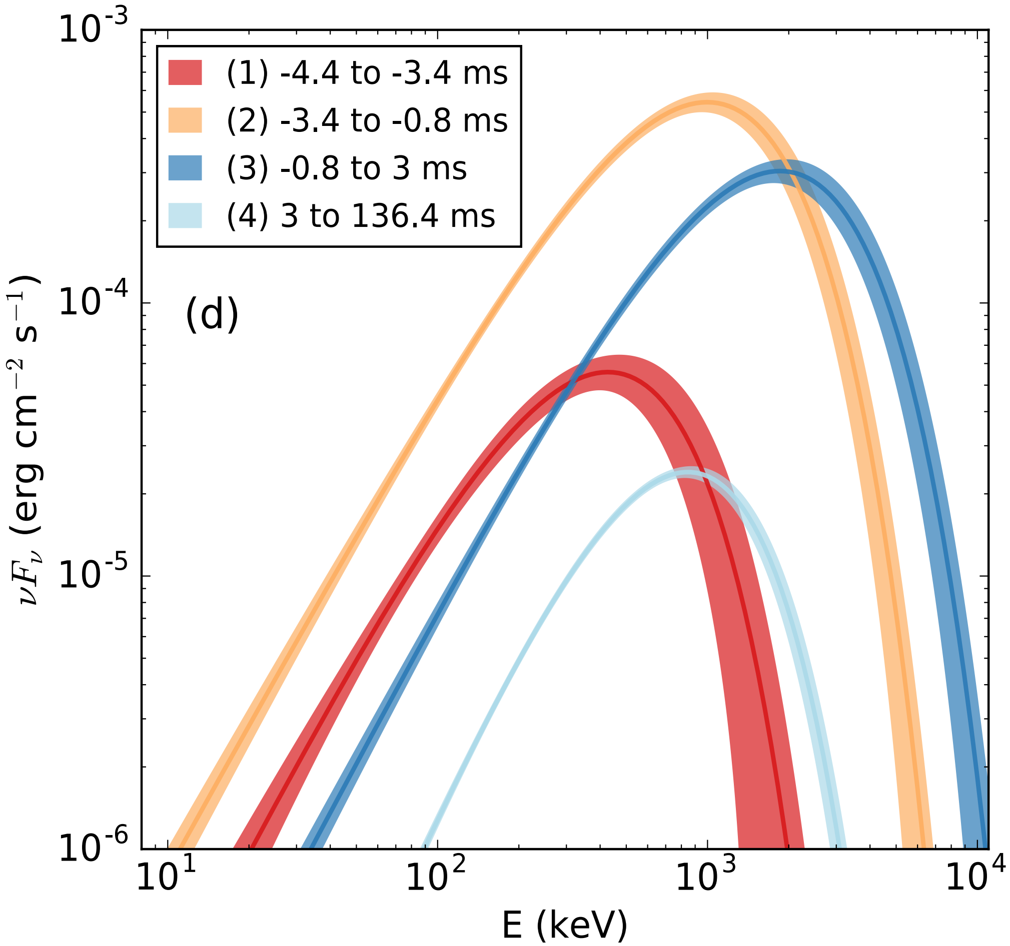
Delayed GeV-band "nebular" emission detected by *Fermi*-LAT.



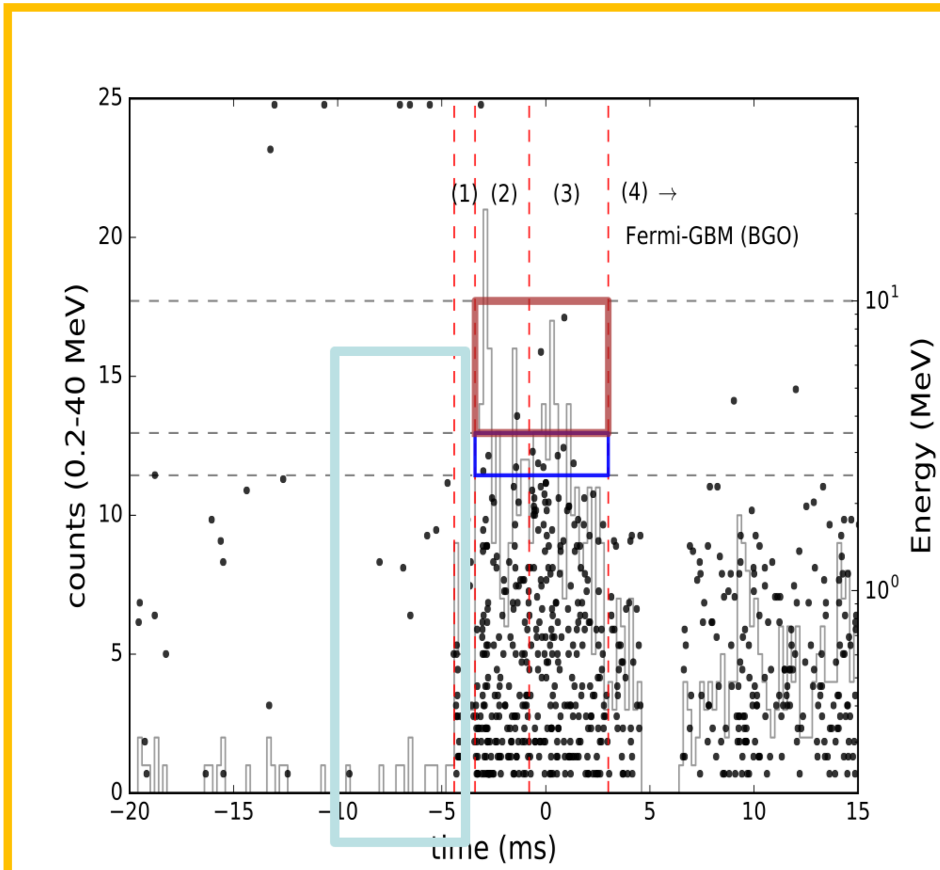


Further Details: O.J. Roberts et al., Nature (2021): http://doi.org/10.1038/s41586-020-03077-8

GRB 200415A: *Fermi*-GBM and *Swift*-BAT



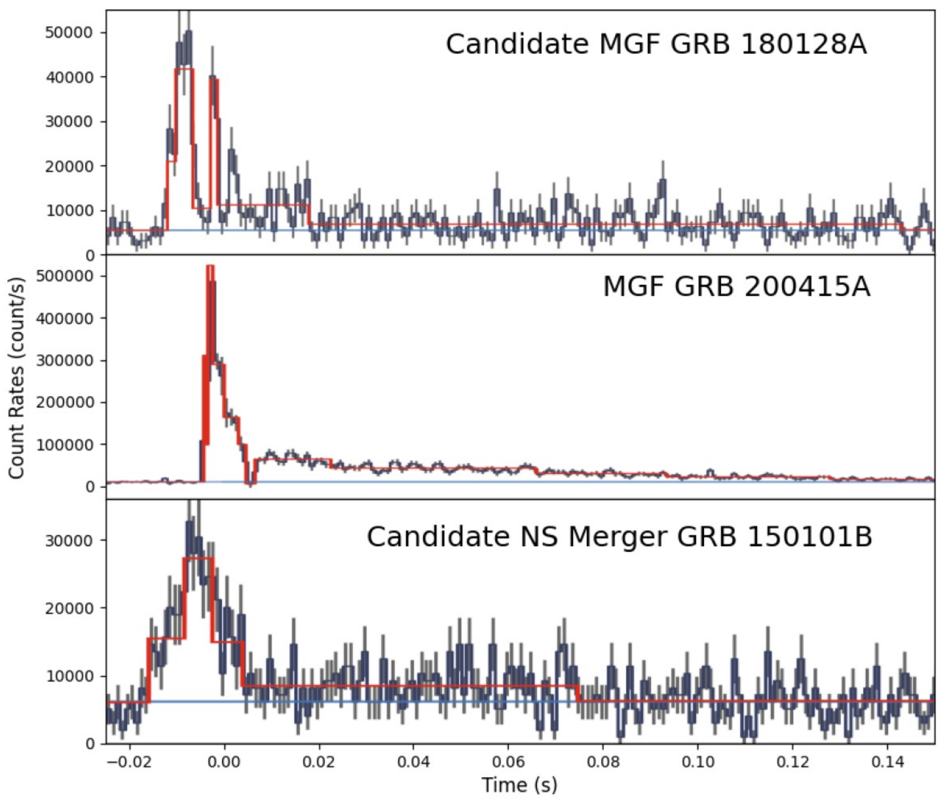
Non-thermal, **Comptonized spectrum** throughout evolution of the initial spike.

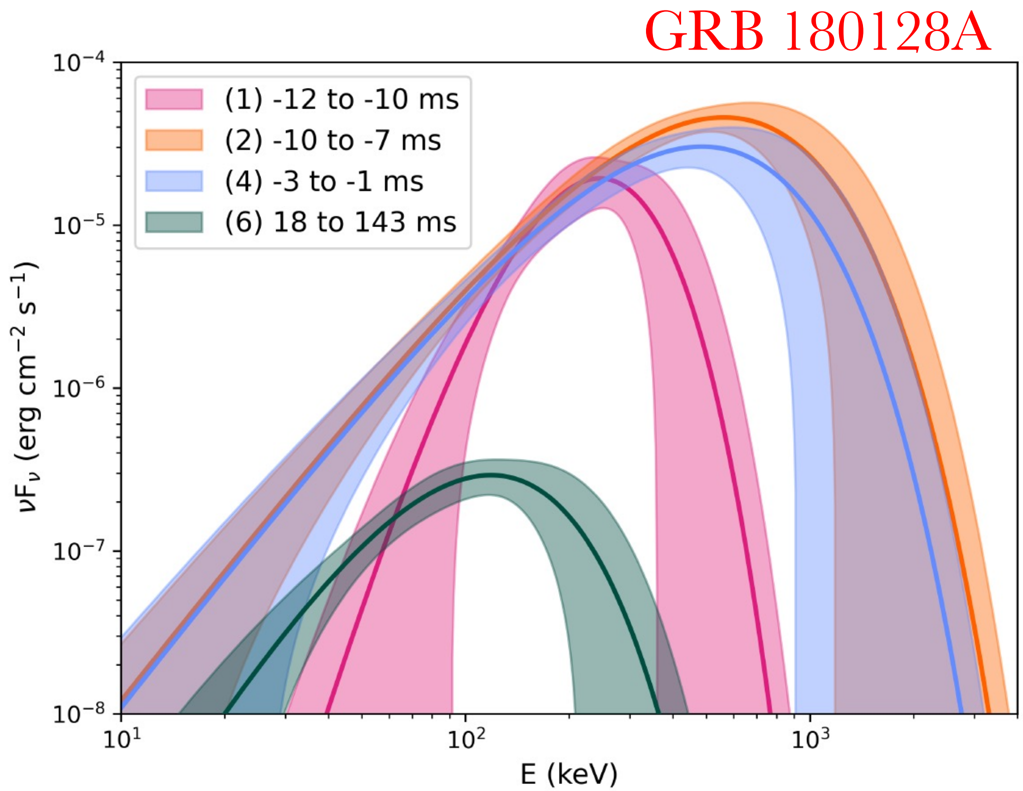


Maximum prompt photon energy Is 3 MeV => $\Gamma > 6$ for transparency to $\gamma\gamma \to e^+e^-$.

O.J. Roberts et al., (2021) Nature: [*http://doi.org/10.1038/s41586-020-03077-8*](http://doi.org/10.1038/s41586-020-03077-8)

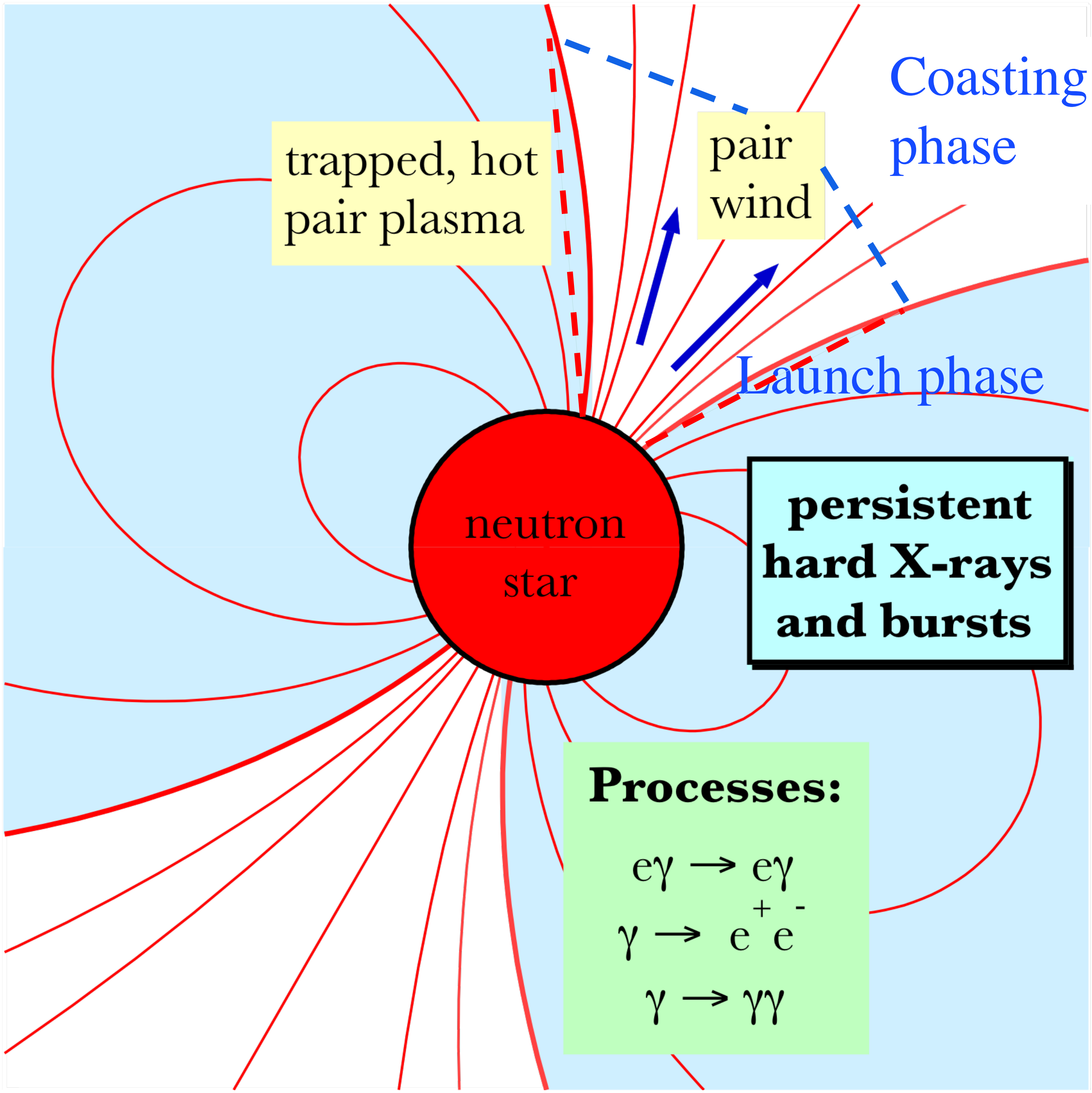
GRB 180128A: another Sculptor MGF





- *Left*: light curves for GRBs 180128A and 200415A from NGC 253, and an NS-NS merger short GRB from a z=0.134 galaxy.
- *Right*: COMPT spectral evolution of GRB 180128A.
- Trigg et al., A&A, 687, A173 (2024). *See also Trigg talk for GRB 231115A in M82.*

Magnetar Giant Flare Geometry

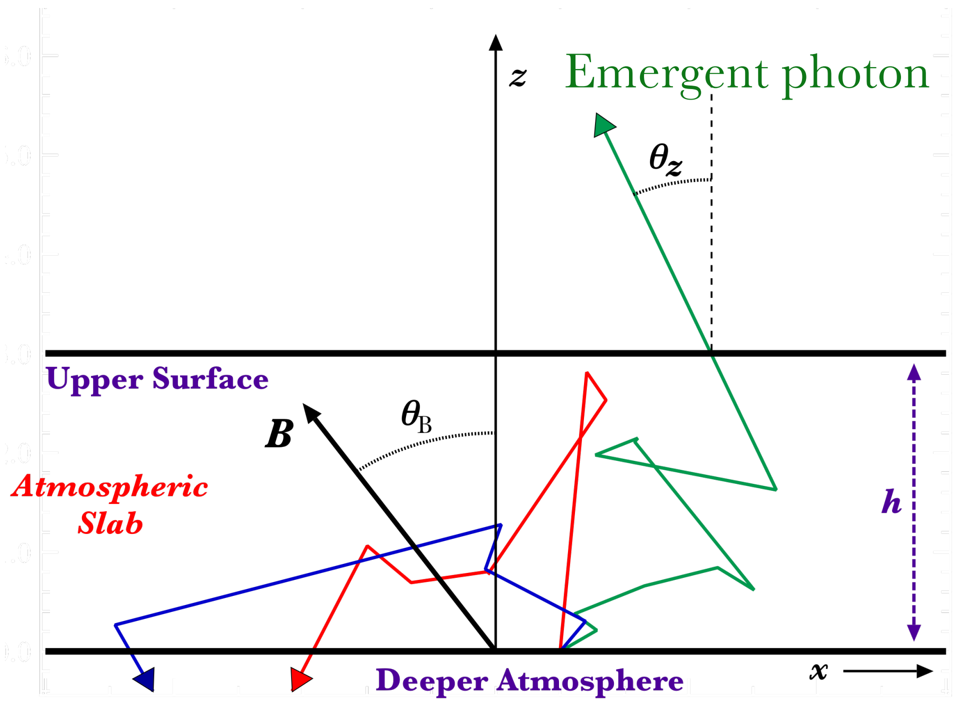


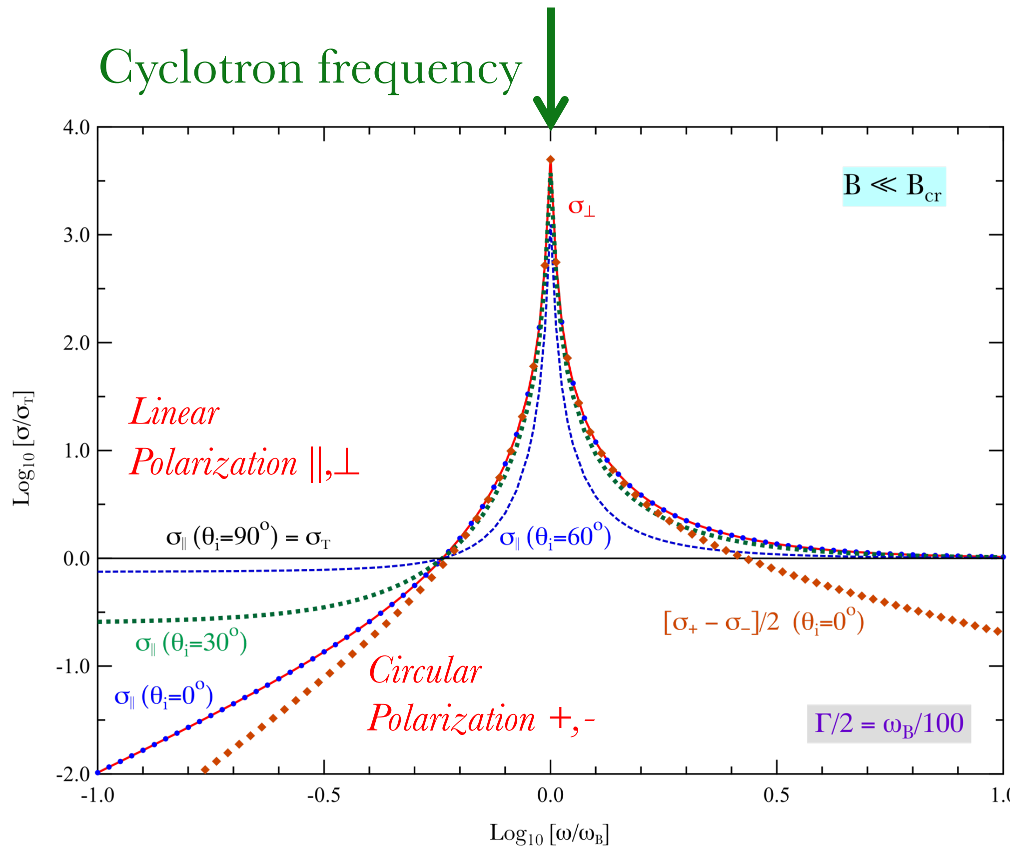
Giant Flare Model

- Pair wind is treated in coasting phase (fixed Γ) only – no dynamics yet.
- Field line is strongly-twisted, split-monopole morphology ($B \propto r^{-2}$) near the pole; dipolar flared field lines generate similar results.
- Adiabatic cooling of pairs is treated in conical geometry with radial field lines. Then $\rho_e \propto A^{-1} \propto B \propto r^{-2}$.
- Non-relativistic EOS for pairs is assumed after onset of cooling, so cooling scales as $T_{eff} \propto P \propto \rho_e^{5/3} \propto r^{-10/3}$ with radius.
  - $kT_{eff,s}$ near stellar surface is set to match peak $E_p \sim 1$ MeV.
- Radiation spectrum is COMPT model $E^{\beta} \exp(-E/kT_{eff})$ in plasma frame, with index $\beta \sim 0$ fixed throughout the wind sheath.
- Radiation anisotropy is from a scattering transport MC simulation.
- Spectrum and angular profile are Doppler boosted to all sky directions.

Scattering Transport in Wind

From: Barchas, Hu & Baring, MNRAS **500**, 5369 (2021).

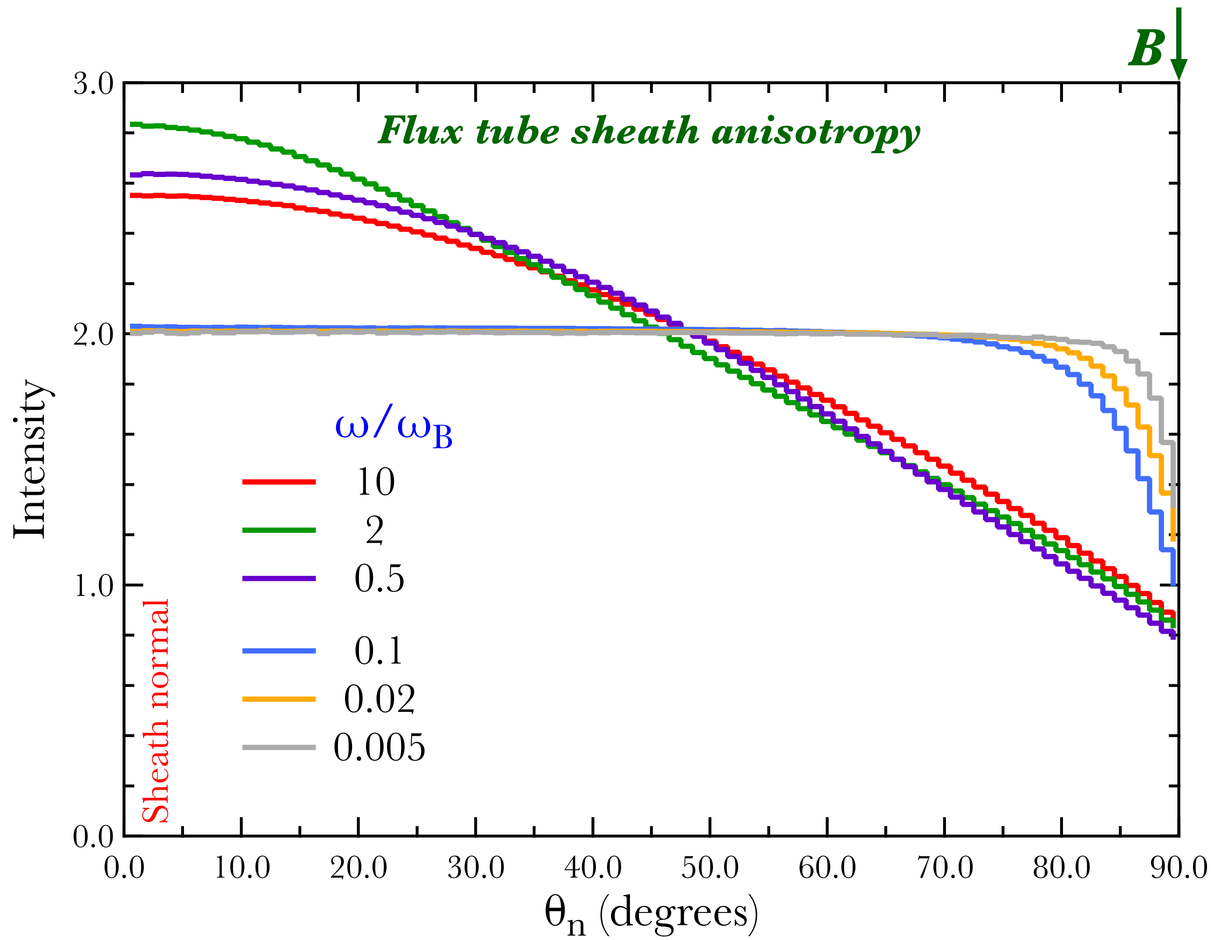




- *Left*: slab geometry for magnetic Thomson scattering transport in local atmospheres or wind zones for neutron stars. The Monte Carlo simulation is *MAGTHOMSCATT*.
- *Right*: magnetic Thomson scattering cross section with its prominent cyclotron resonance. The cross section of the O-mode (||) is strongly suppressed below the cyclotron frequency $\omega_B = eB/m_ec$ for photons beamed almost along ***B*** ; same is true for the X-mode (⊥).

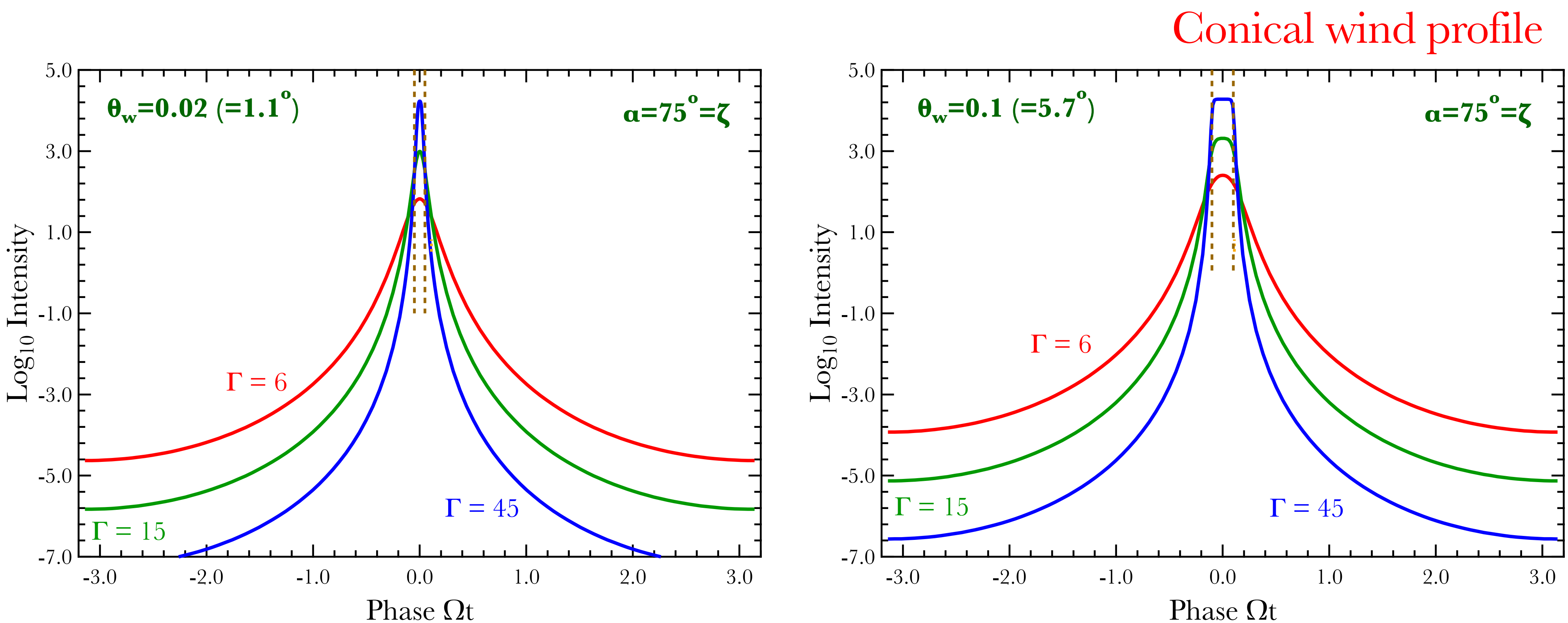
Anisotropy in Wind Sheath

In plasma rest frame



- Intensity distributions from *MAGTHOMSCATT* as a function of the angle θ_n normal to the wind's external surface (sheath). Dinh et al. (in prep.)

Intensity Light Curves



- Rotational phase profiles spanning a period P for a conical MGF wind of small (left, θ_w=1.1°) and moderate (right, θ_w= 5.7°) solid angle. Larger solid angles enhance probability of MGF detection.
- θ_w is the wind cone's half-angle. Dashed vertical lines mark roughly the effective duration (T_{90}) of the MGF initial "spike," which anti-correlates with the wind's bulk Lorentz factor Γ.

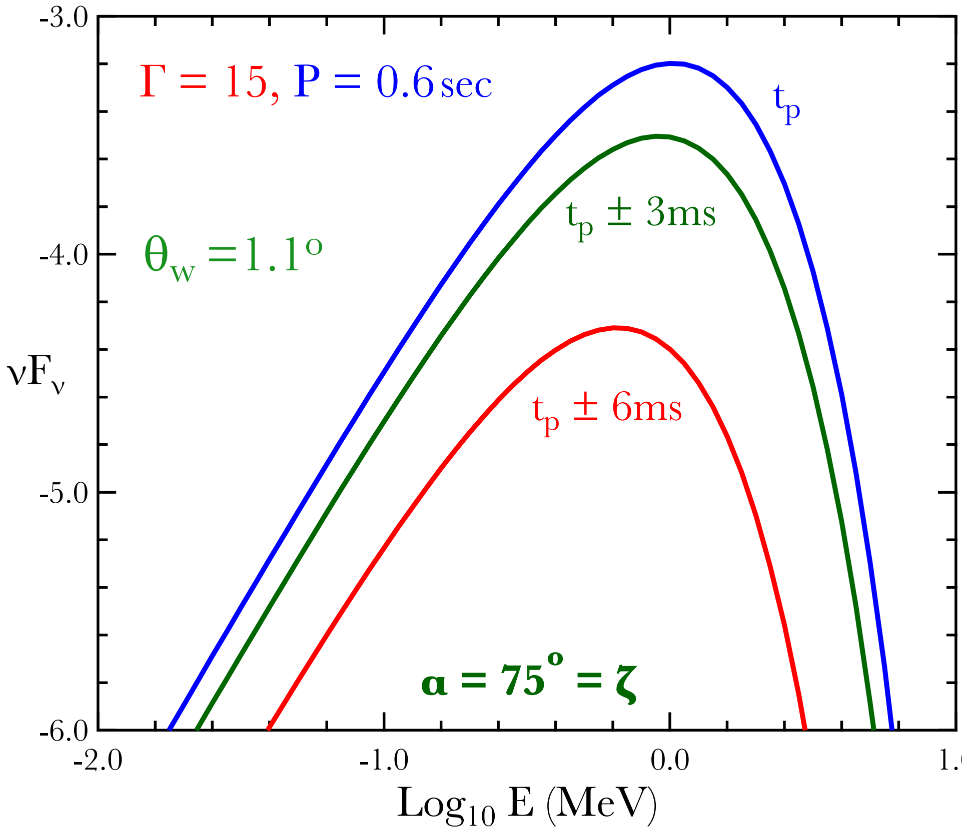
Magnetar Period Estimates

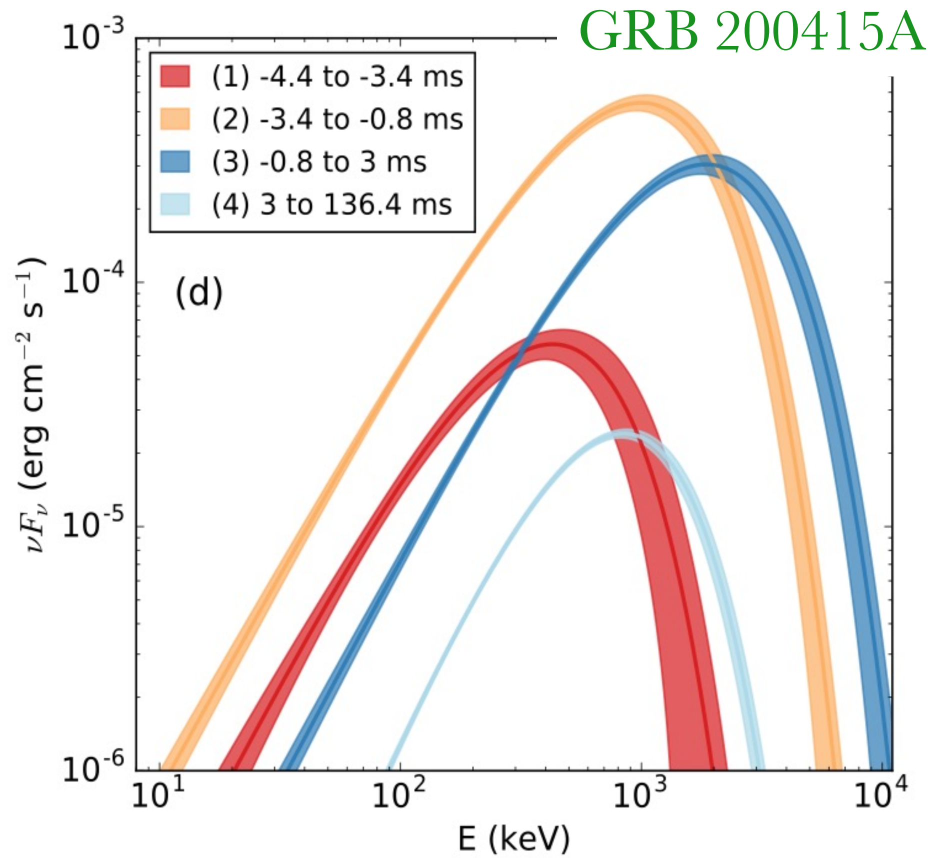
Table 1: Estimated periods for Sculptor GF Magnetars

	Magnetar	GRB 180128A	GRB 200415A
	$T_{90} =$	15 msec	10 msec
	Γ	P (sec)	P (sec)
$\theta_w = 1.1°$	6	0.5	0.3
$\theta_w = 1.1°$	15	0.9	0.6
$\theta_w = 1.1°$	45	2.6	1.7
$\theta_w = 5.7°$	6	0.3	0.2
$\theta_w = 5.7°$	15	0.4	0.3
$\theta_w = 5.7°$	45	0.5	0.4

- For these two wind opening half-angles, the rough P values are nearly all somewhat shorter than known magnetar periods. Structured winds complicate.
- For Γ=100, the deduced periods are around a factor of 2 higher than for Γ=45.

MGF Spectral Evolution





- Coasting outflow (Γ=15) with adiabatically cooled COMPT spectrum. Surface emissivity modeled with output from radiative transfer code (see poster by Wadiasingh et al. for magnetar normal bursts). No wind dynamics included yet. Strong-twist field geometry is assumed. Model rotation period is P=0.6 second.
- Temporal asymmetry of 200415A spectroscopy suggests that data encapsulates onset of coasting and acceleration phase and/or injection abatement.

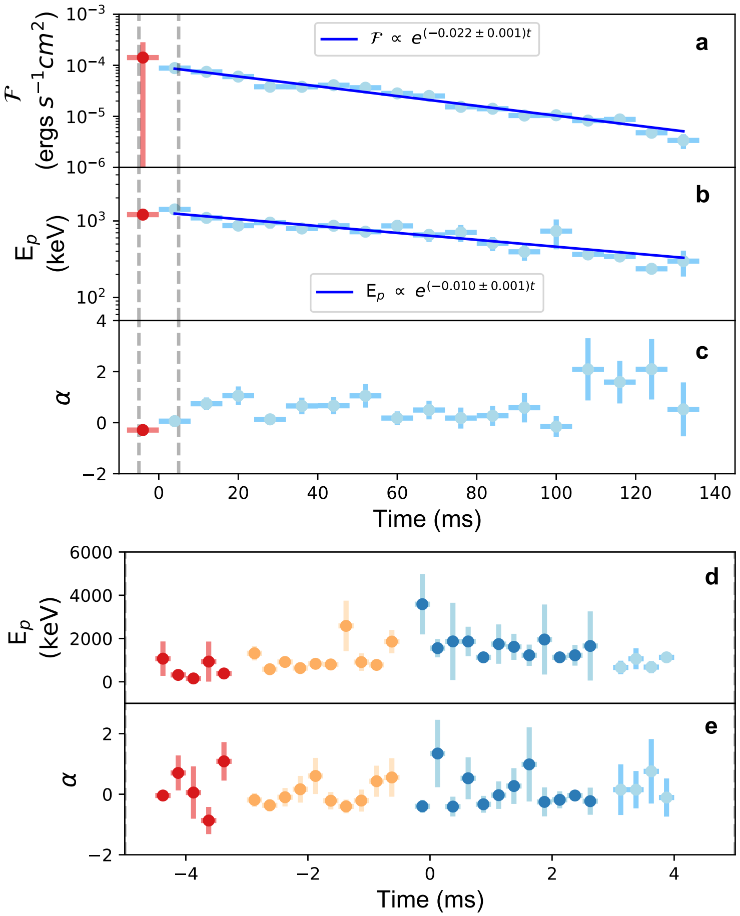
Conclusions

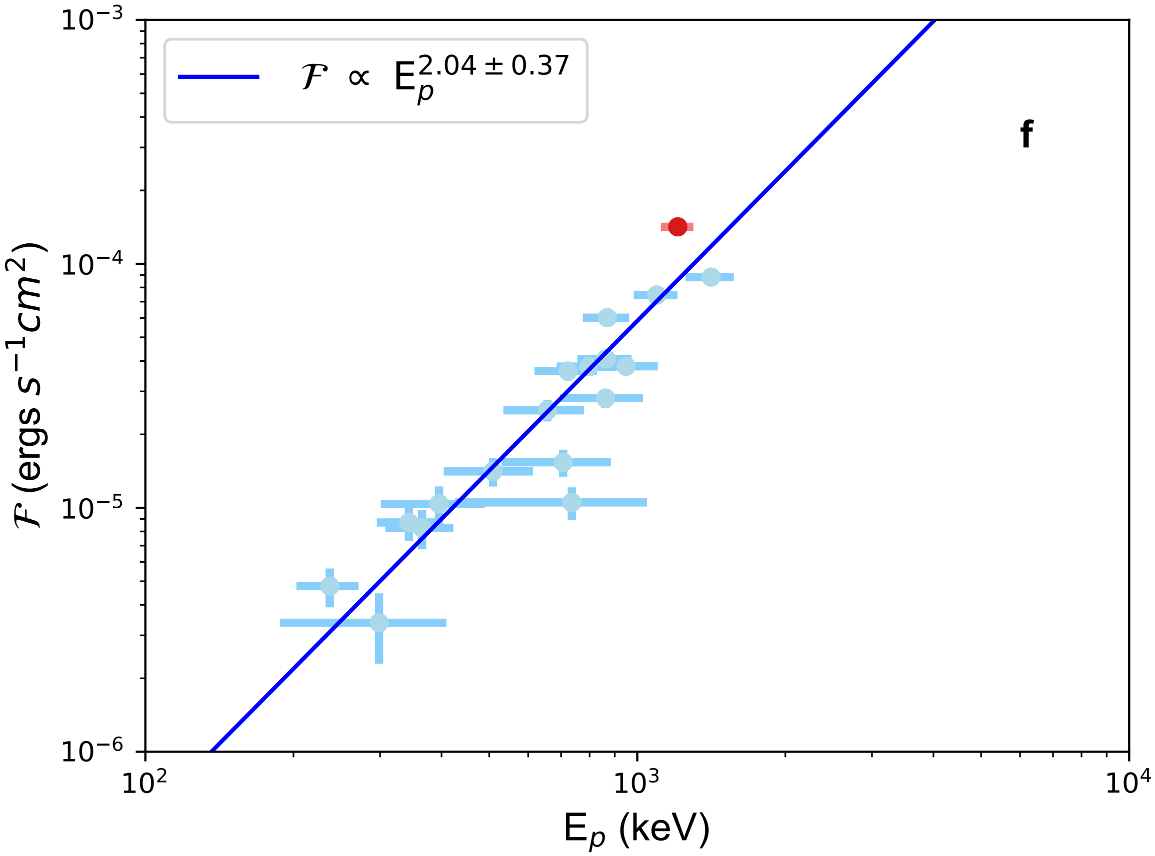
- The rapid rise and spectral hardening is well described by Doppler boosting/beaming elements. Details such as magnetic field morphology and pair EOS are secondary/minor influences.
- Inferred rotational period is short, unless $\Gamma = 100$.
- Asymmetry of the observed spectral evolution indicates either
  - i) the wind is strongly asymmetric in its $\Gamma(\theta)$ profile (why?);
  - ii) the engine is abating as the wind cone sweeps across our LOS (more likely).
- ***To do***:
- Next task is to introduce wind dynamics to determine the $\Gamma(r)$ profile and assess if acceleration phase modifies spectral evolution from the pure coasting case.
  - Radiation pressure tensor has already been delivered in an RTE analysis in high $\boldsymbol{B}$.
  - With dynamics in, we can assess inferences of energy injection abatement.
  - Can also better explore luminosity-peak energy correlation (Trigg talk).
- Eventually hope to replace magnetic Thomson physics by full QED Compton cross section (Gonthier lead).

Appendix of Slides

Spectral-Flux Correlations

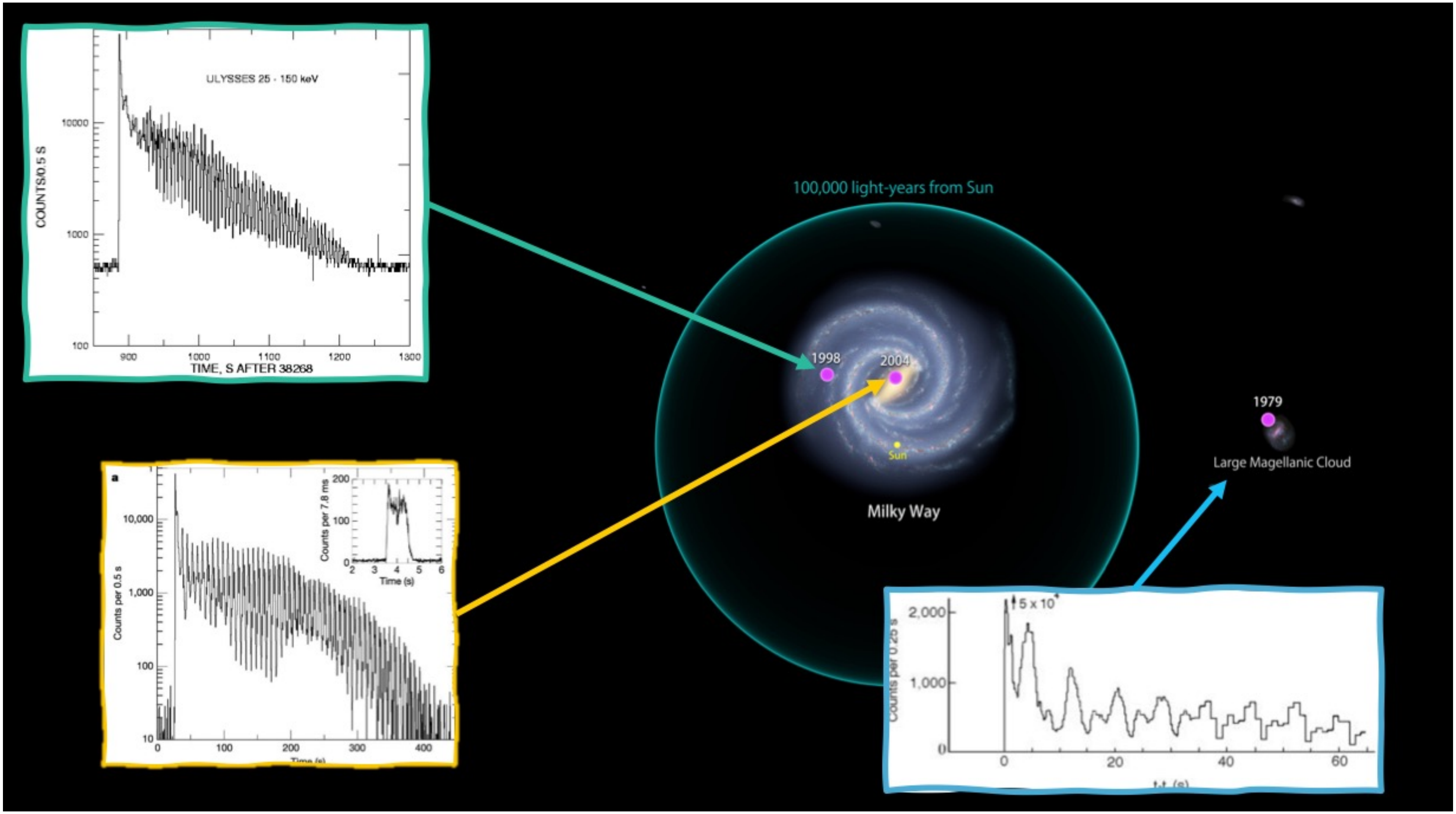
Roberts et al. Nature **589**, 207 (2021).



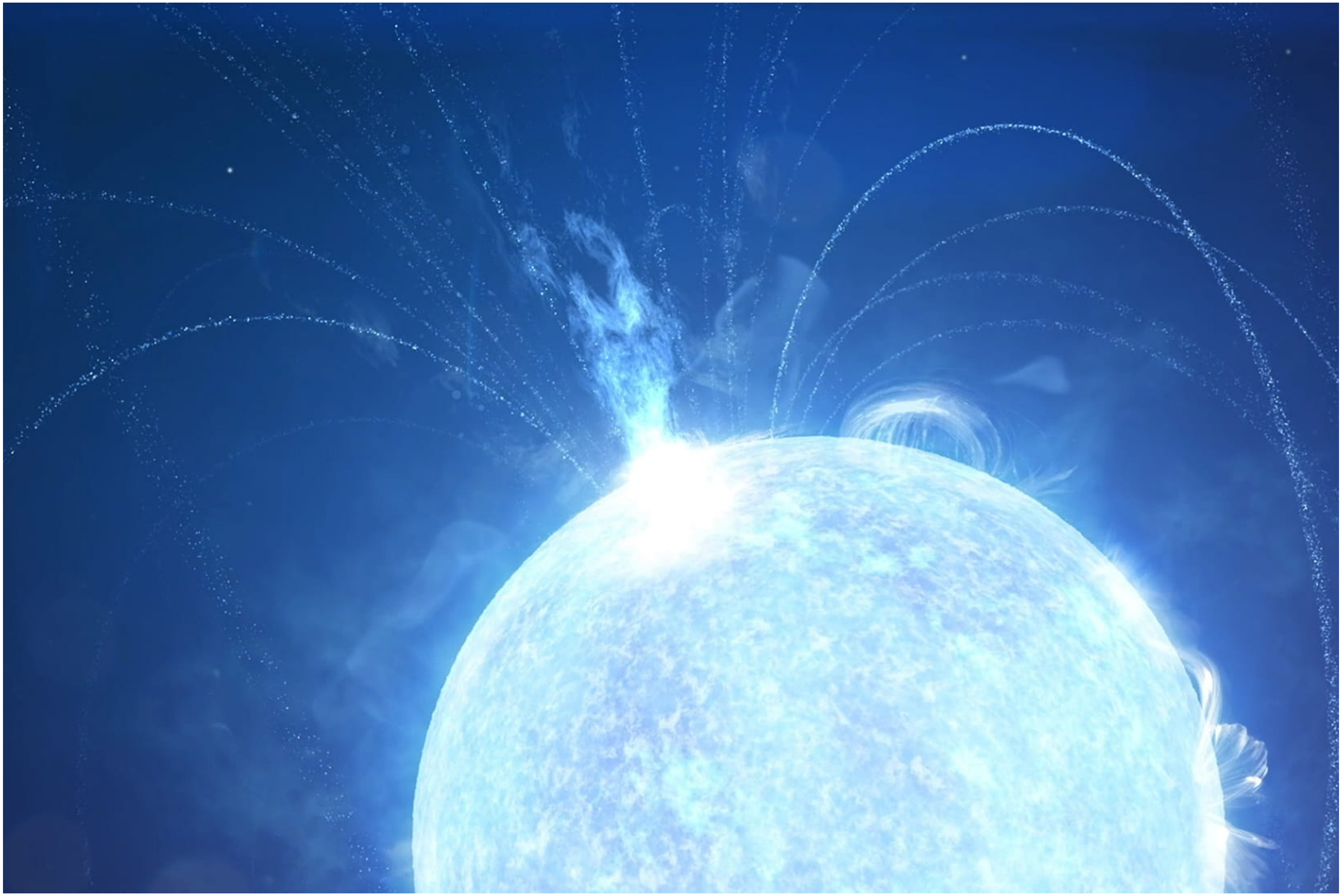


- Spectral peak energy couples to instantaneous Doppler factor via E_p α δ.
- Flux F is integrated over largish areas and so couples as F α δ^2.
- Combined, the temporal-spectral variability is described by F α $(E_p)^2$.

Magnetar Giant Flares are rare



Crust Ruptures → Photon Torpedo



Credit: NASA