What's Wrong with the Idea that CME-Shock Particles Produce 100-MeV γ Rays?

James M. Ryan[1], A. Bruno[2], G. de Nolfo[3], S, Dalla[4], A. Hutchinson[2], I. Richardson[3]
[1]UNH, [2]CuA, [3]GSFC, [4]UCLAN

University of New Hampshire

Introduction

Long Duration Gamma Ray Flares (LDGRF) (Akimov *et al.*, 1991) were first recorded as such three cycles ago. They have puzzled researchers since. Not only are the γ emissions prolonged (hours) and delayed (tens of minutes), they are very energetic (> 1 GeV). The identification of prime agent for this phenomenon has settled on either (1) CME-associated shocks, in which the accelerated particles are transported back to the Sun, or (2) trapping and acceleration takes place in a large coronal loop. The superficial resemblance of SEP events to Ground Level Enhancements (GLE), *i.e.*, high energy and extension beyond the flare's impulsive phase, has focused the attention of many trying to explain LDGRFs in terms of GLE-associated or related SEP events.

However, given that much of this process takes place without *in situ* measurements or images, attributing LDGRFs to CME shocks requires more than a superficial resemblance. In particular, we need first a schematic model of the process, secondly a theoretical and quantitative version of that model, quantitative attention to outlier events, and the absence of unambiguous counter examples.

The Big Picture

The key features of the most theoretically challenging LDGRFs are:

- Time extended (up to hours) γ-ray emission >100 MeV, indicative of pion decay,
- Onset delays of the hi-E emission of tens of minutes from the impulsive phase,
- Wide area emission to accommodate over the limb events.

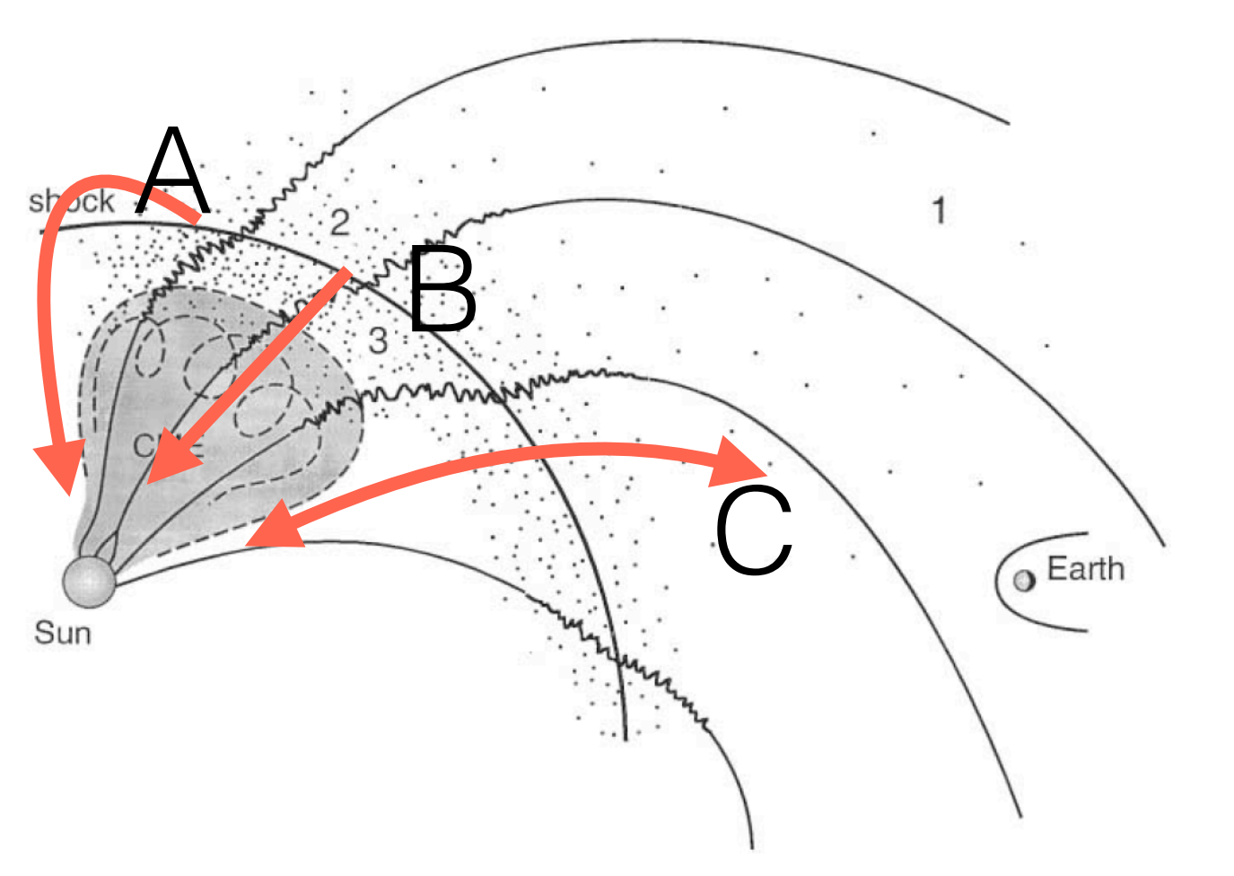

Fig. 1 Courtesy of M.A. Lee

Fig. 1 illustrates the three possible pathways for the transport of energetic protons or ions to the Sun.

A. Particles (some) from the shock front find a relatively scatter-free fieldline(s).
B. Through the turbulent downstream region, the sheath and CME body. Unpredictable paths at lower altitudes.
C. Acceleration at the flanks, not the nose.

Good scientific practice dictates that we search for a simple and consistent solution with no exception (William of Ockham, circa 1287–1347). Ideally, we gain insight into new observations that either support or reject the hypothesis.

Problems Awaiting Solution

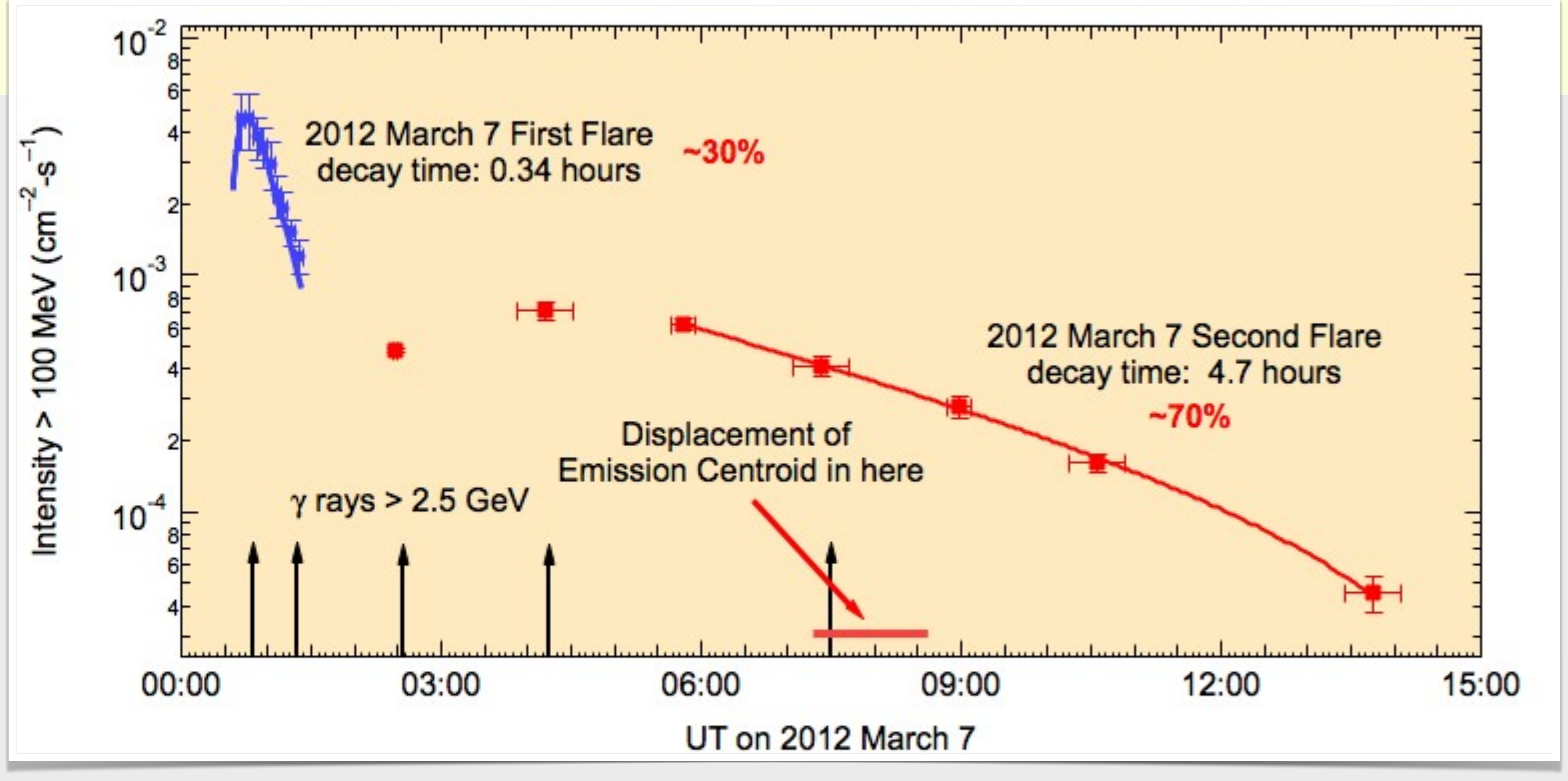

Fig. 2. The Fermi-LAT data from 2012 March 7 resolved into two independent events, illustrating key features and several problems with a CME-shock origin (Ajello et al. 2014).

1. Correlations of the number of detected particles in space and the number deduced from the γ ray measurements are frequently employed. However, none has achieved a level of consensus (de Nolfo *et al.*, 2019; Bruno *et al.*, 2023; Gopalswamy *et al.* 2021). The reasons vary from use of different catalogs, data selections, magnitude corrections, shock crossing number, among other things. At best the correlations succeed only on a logarithmic basis. On an absolute scale, variations of up to two orders of magnitude persist, suggesting little, if any causal relationship, *i.e.*, the Big Flare Syndrome (Kahler 1982), (Fig. 3). Correlations with proxies fare no better, *e.g.*, CME properties, Type II emission and onset delays (Bruno *et al.* 2023).

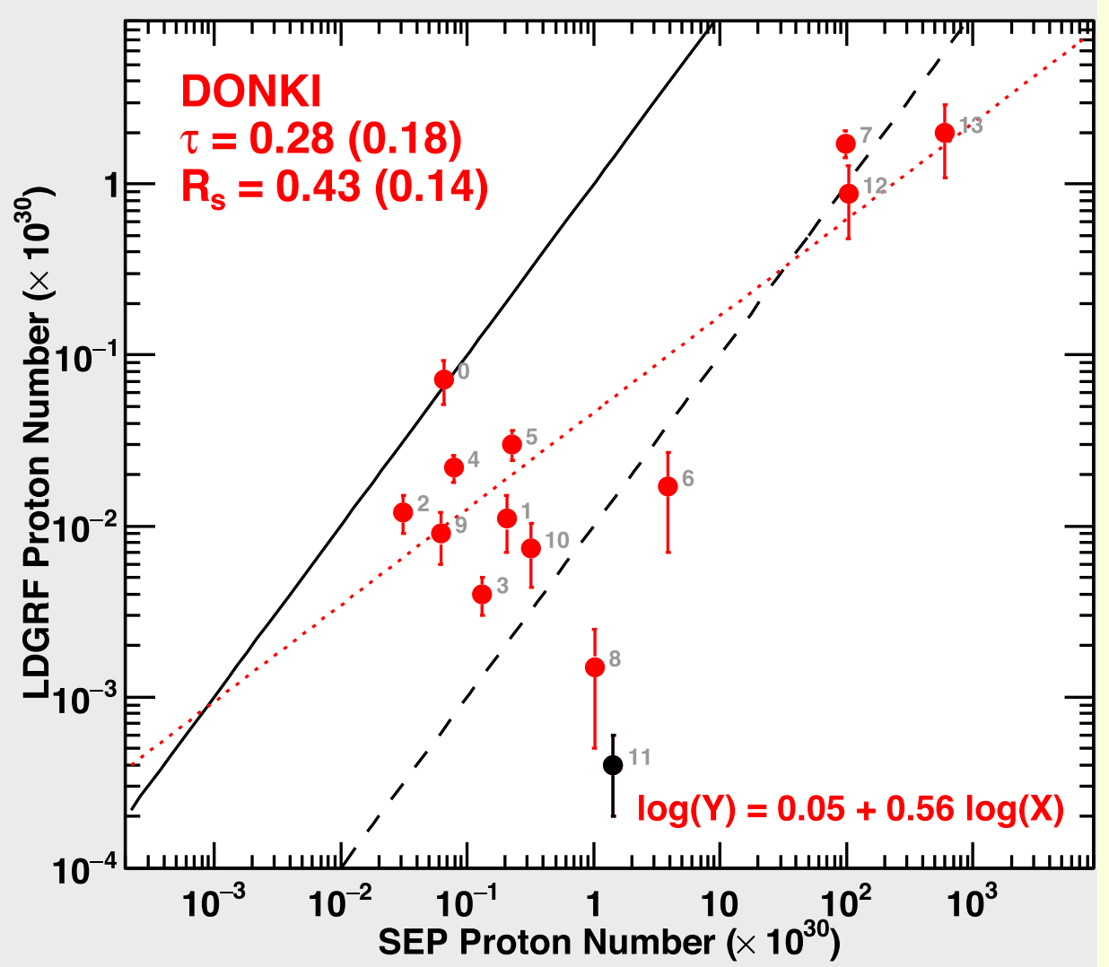

Fig. 3 Log correlation plot of "flare" particle number vs. in space >500 MeV using DONKI catalog (Bruno *et* al. 2023).

2. Gamma-ray energies frequently exceed those of GLE particles (Bruno *et al.* 2019). The >2.5 GeV photons in Fig. 2 require protons of considerably higher energy.
3. For Path C in Fig. 1, we should expect GLEs to be distributed over a very wide range of longitudes and poorly connected to the nose of the shock.
4. For Path B, achieving a remarkably smooth decay over hours (see Fig. 2 and Ajello *et al.* 2014, Omodei *et al.* 2018) will be difficult in the environment behind the shock, which includes the sheath and compression-enhanced turbulence (Bruno et al. 2023).
5. For Path A, because the shock moves rapidly, connecting and disconnecting from open field lines, achieving a stable set of scatter-free field lines for a fraction of a day is questionable.

6. When energetic neutrons are detected and *measured*, their emission profile exhibits *no delay* w.r.t. the impulsive phase, rendering time delay analyses moot. It is akin to protons being accelerated continuously and when the energies are great enough, pions (and hi-E γ rays) are produced. In Fig. 4 are the COMPTEL velocity corrected 9-100 MeV neutron data of the 1991 June 11 flare. Hi-E neutrons are continuously being produced with γ rays emerging 10 minutes later at 0213 UT.

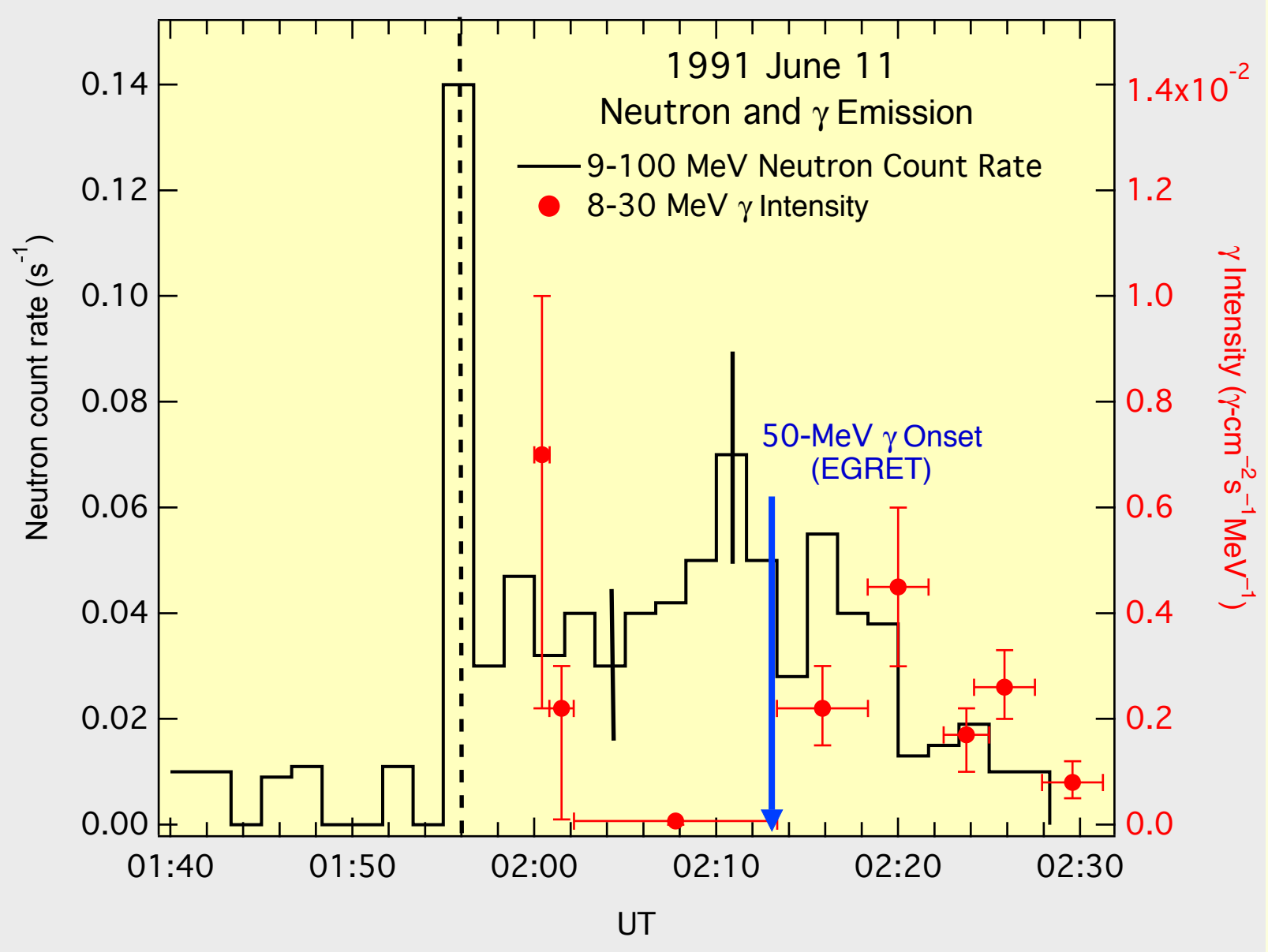

Fig. 4 Ryan *et al*, 2024

7. What do we do with CMEs that have no shock or associated LDGRF? Or LDGRFs with few, if any SEPs, *e.g.* 2011 March 7 (Winter *et al.* 2018).
"*On the other hand, the 2012 May 17 GLE event was not linked to one of the larger LDGRFs, and some of the high-energy SEP events measured by…PAMELA… were not associated with LDGRFs; analogously, several LDGRFs were accompanied by relatively small SEP events (de Nolfo* et al. *2019). Finally, while characterized [as] one of the longest γ-ray emissions, no significant flux of high-energy SEPs was measured during the 2011 March 7 event…*" (Bruno *et al.* 2023)

8. How do we explain the three homologous LDGRFs from 1991 June 9-15 from the same active region, that exhibit identical morphologies, including durations and decay times for both phases of each event (Rank *et al.*, 2001)? In Fig 5 are the neutron-capture 2.2-MeV line intensities from these events. All three exhibit the same general profile and were all strong LDGRFs.

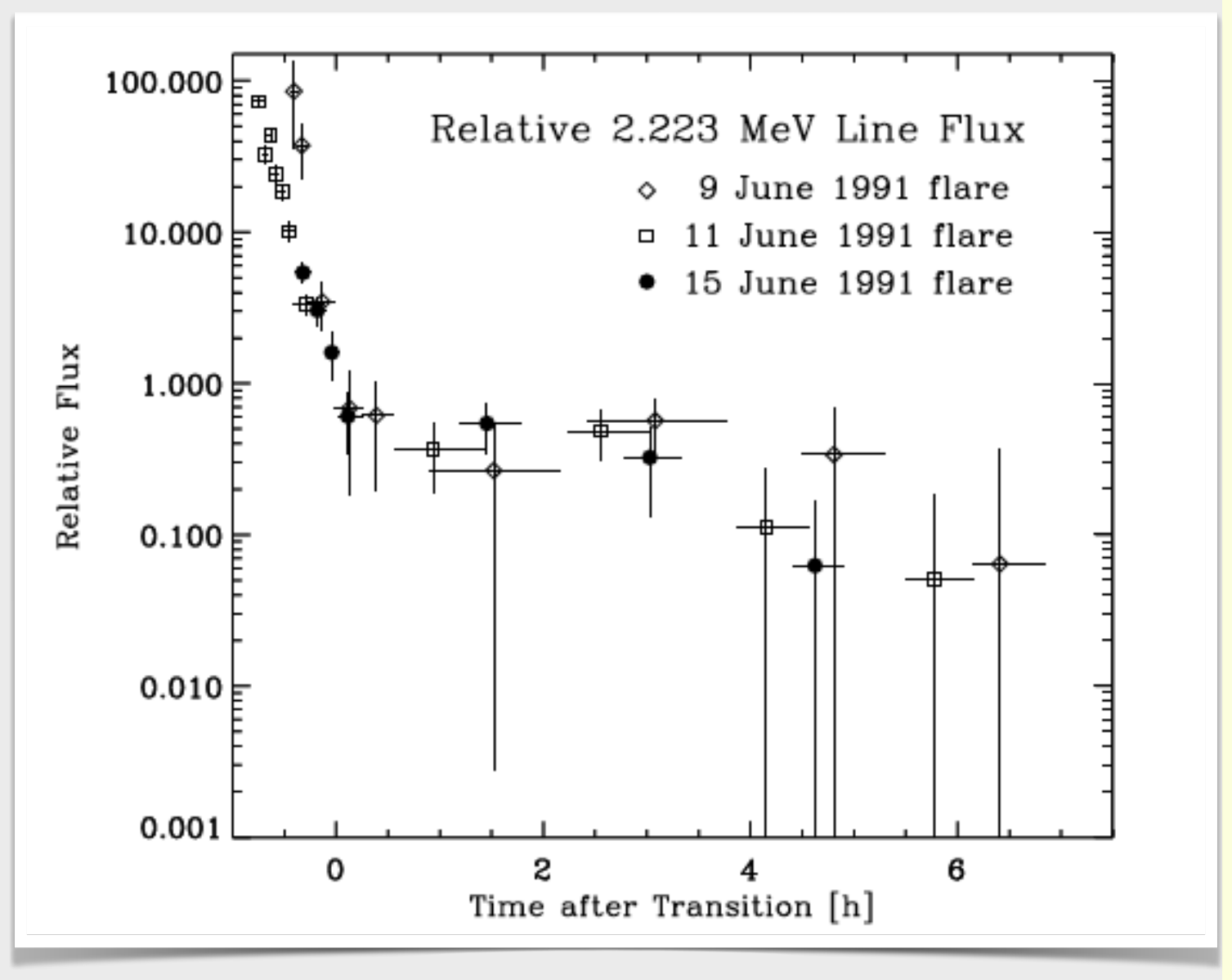

Fig. 5 Rank et al. (2001)

Date	v_{sh} [km s^{-1}]	C2 time [UT]	D [h]	r_{fin} [$R_\odot$]	$\overline{P}$ (r_{ini} = 1.20 $R_\odot$) [%]
2011-Mar-07	2125	20:00:05	10.1	103.6	0.603
2012-Jan-23	2175	04:00:05	5.2	57.5	0.667
2012-Mar-05	1531	04:00:05	3.6	29.2	0.800
2012-Mar-07 $^{(a)}$	2684	00:24:06	19.5	228.6	0.555
2012-Mar-07 $^{(b)}$	1825	01:30:24	19.5	158.4	0.574
2012-Mar-09	950	04:26:09	3.8	19.7	0.932
2013-May-13	1850	16:07:55	3.8	36.7	0.745
2013-May-14	2625	01:25:51	5.4	71.5	0.640
2014-Feb-25	2147	01:25:50	6.6	70.9	0.640

9. For A, B and C, the impeding mirror force, even with some scattering to help, seldom produces satisfactory precipitation, especially for great distances or time after the impulsive phase. This is in stark disagreement with events with large numbers of "flare" particles compared to those in the accompanying GLE, *e.g.*, 2012 March 7. The table above summarizes transport calculations for several large and prolonged events. With a m.f.p. of 0.1 AU, none exceeds a precipitation fraction of 1% (Hutchinson et al. 2022).

Discussion

We have the conflicting requirements that (1) we must contain the particles in a large volume over a long enough time to accelerate them without losing them and (2) once they are lost from that acceleration volume, there must be numerous, efficient and reliable routes for them to precipitate, (Ming Zhang, priv. comm.).

This is what we have now for GLEs, where particles, after being accelerated, break free of the shock onto well connected (to Earth), turbulence-free field lines.

We would be better served with a LDGRF model of a low altitude, stationary acceleration site with predictable losses to the solar surface. The long duration feature of an LDGRF suggests a large volume, that in turn reduces the need for long term, unusually efficient acceleration in a small volume. 2nd order Fermi acceleration in a leaky-box coronal loop of order 1 $R_\odot$ is such an environment. Active loops of dimension $>10^{10}$ cm have been recognized by Pesce-Rollins *et al.* (2024). Wave energy is continually provided from below, *i.e.*, what heats the corona (Ryan and Lee 1991).

Shown in Fig. 1 are the two LDGRFs of 2012 March 7 fit with a trapping/acceleration and diffusive 1-d precipitation model of the form described by Ryan and Lee. The different decay times arise from differing levels of turbulence and loop size, *i.e.*, $\tau_{\text{diffusive loss time}} = L^2(\pi^2\kappa)^{-1}$, where L is the loop length and κ is the diffusion coefficient.

To support this process, theoretical work is necessary to evaluate how much wave energy is required above that already provided by the photosphere.

References

Akimov *et al*. 22nd ICRC, Dublin, 1991.
Ajello *et al*., Astrophys. J., 789.20, 2014.
Bruno *et al*., Astrophys. J., 862.97, 2018.
Bruno *et al*., Astrophys. J., 953.187, 2023.
de Nolfo *et al*., Astrophys. J., 879.90, 2019.
Gopalswamy *et al.*, Astrophys. J., 915.82, 2021.
Hutchinson *et al*., A&A, **658**, 2022.
Kahler, S.W., J. Geophys. Res. **87**, Issue A5, 1982.
Omodei *et al.*, Astrophys. J., 865.L7, 2018.
Pesce-Rollins *et al.* A&A, **683**, 2024.
Rank *et al*., A&A, **378**, 2001.
Ryan and Lee, Astrophys. J., **368**, 1991.
Ryan *et al.*, in preparation, 2024.
Winter *et al.*, Astrophys. J., 864.39, 2018.