Observations of particle acceleration in the solar corona with neutron monitors and radio instruments

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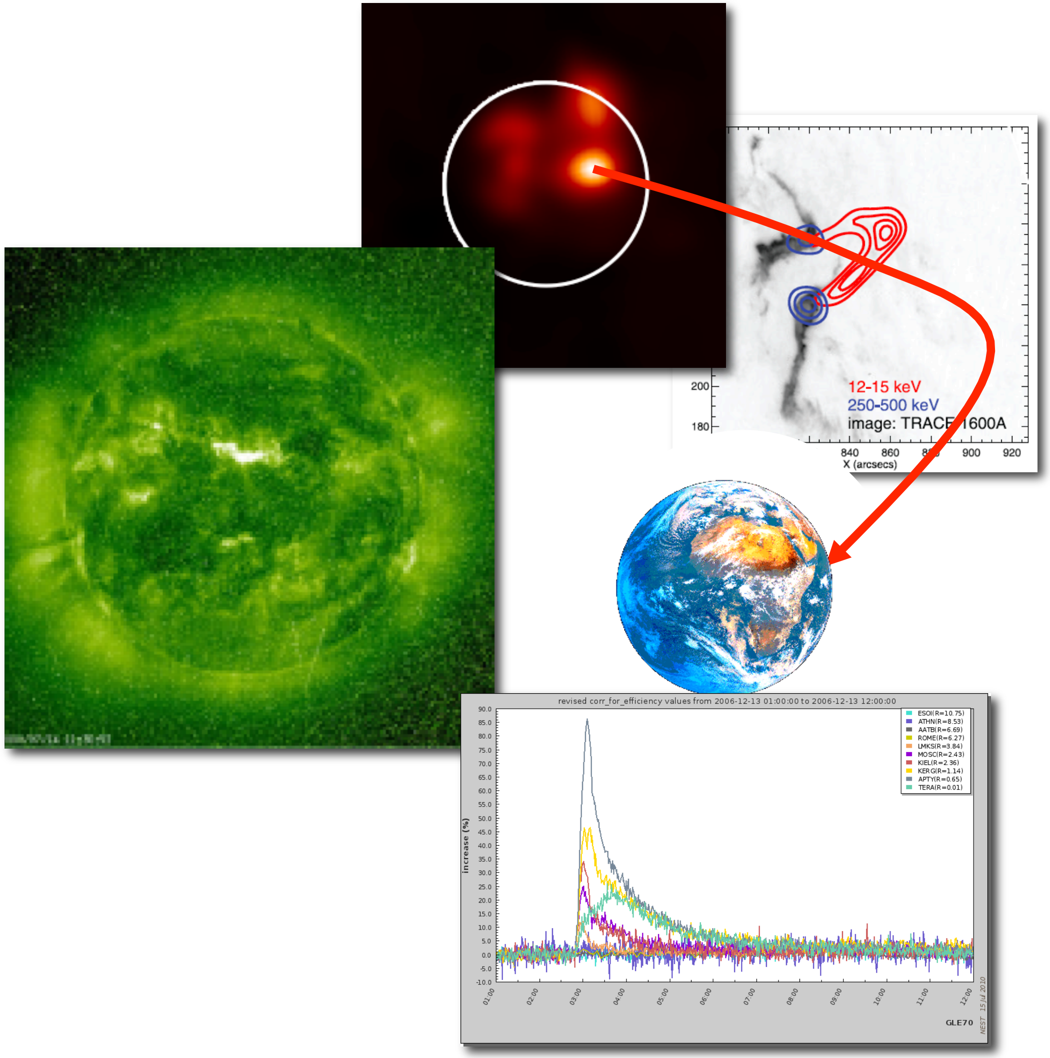


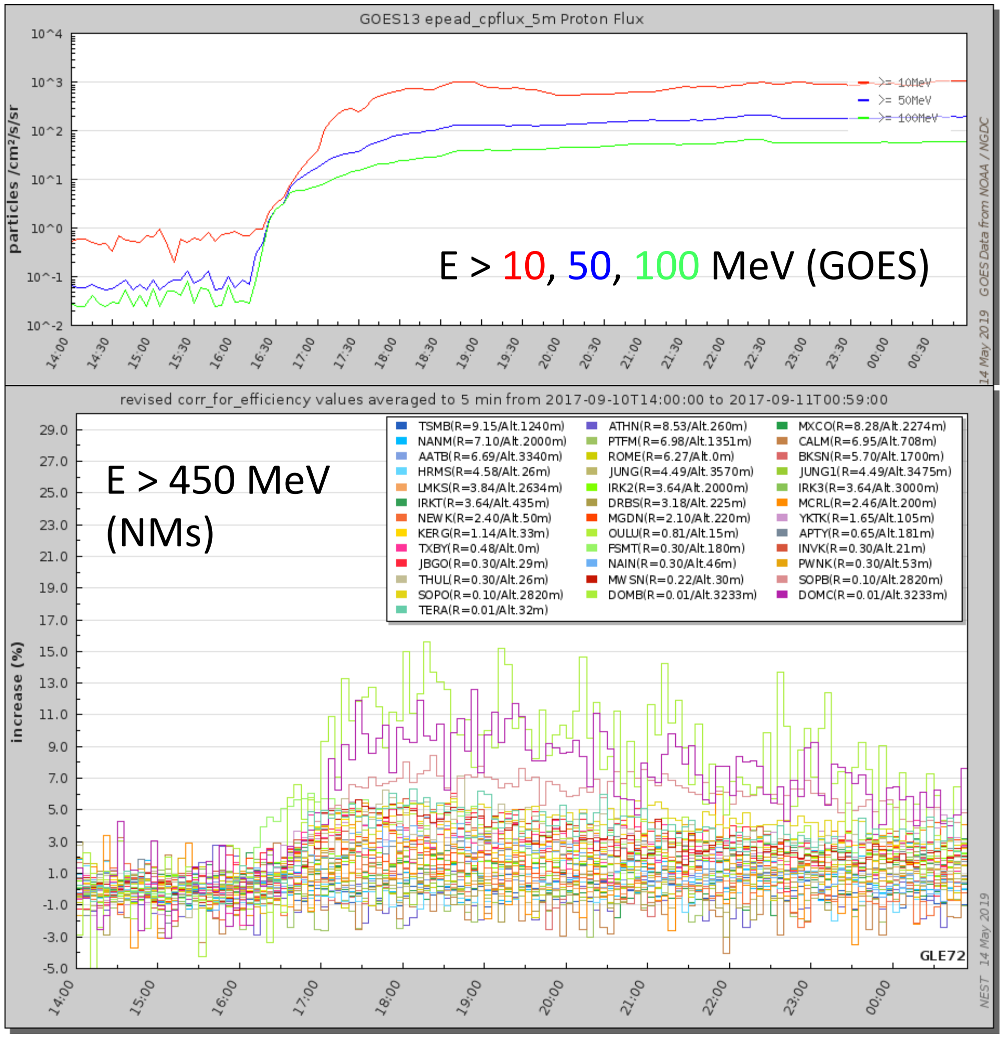
Relativistic solar energetic particles (SEPs) and radio bursts

Outline

- Relativistic proton acceleration at the Sun – an introduction and two simple scenarios
- Release timing of relativistic protons with respect to electron acceleration in the corona (radio emission)
- Summary and questions

Eruptive solar activity associated with GLEs
GLE 20170910

- GLE: "ground-level event" = solar energetic particles > 450 MeV triggering an atmospheric cascade that can be observed down to sea level
- Observation by neutron monitors on ground
- Comparison with measurements at lower energies from space (GOES/NOAA)



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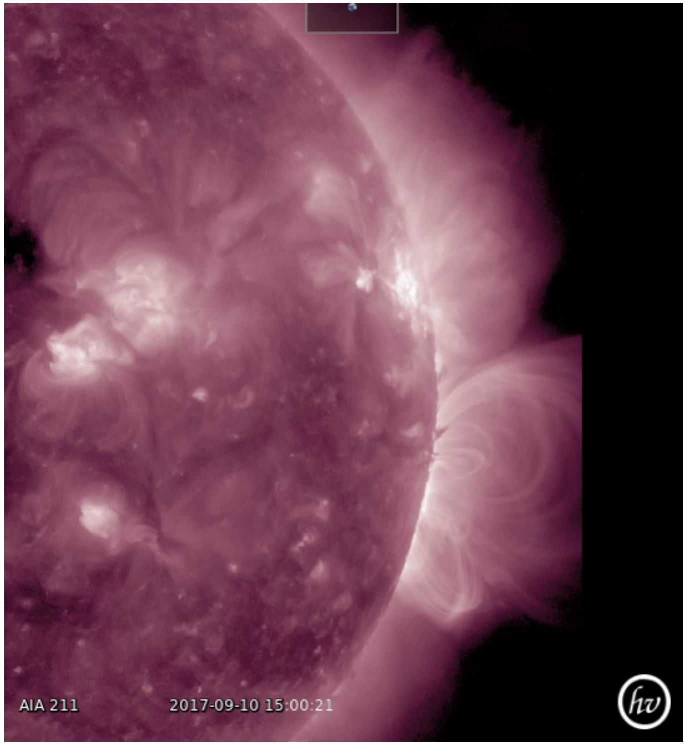
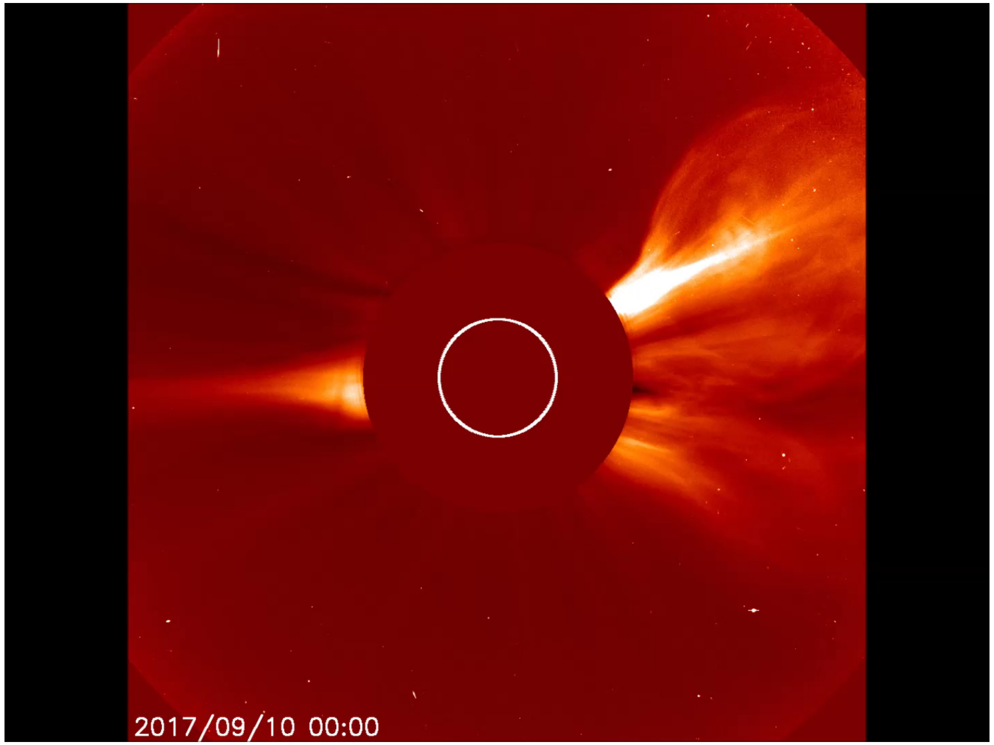
Eruptive solar activity associated with GLEs
White light and EUV imaging: GLE 20170910

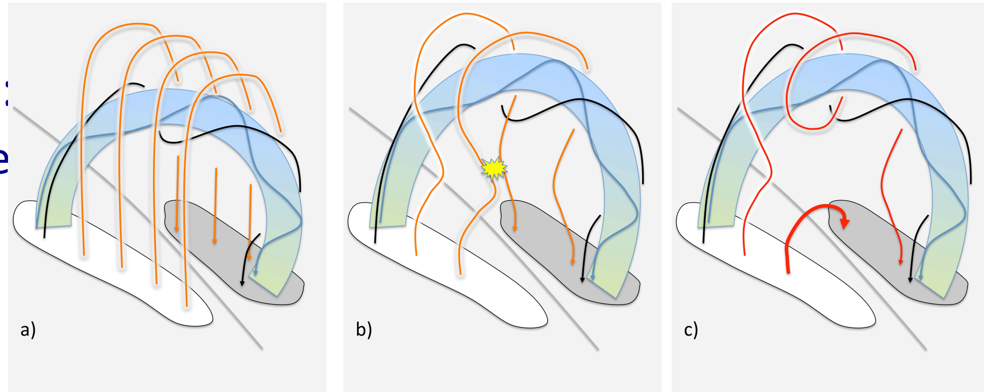




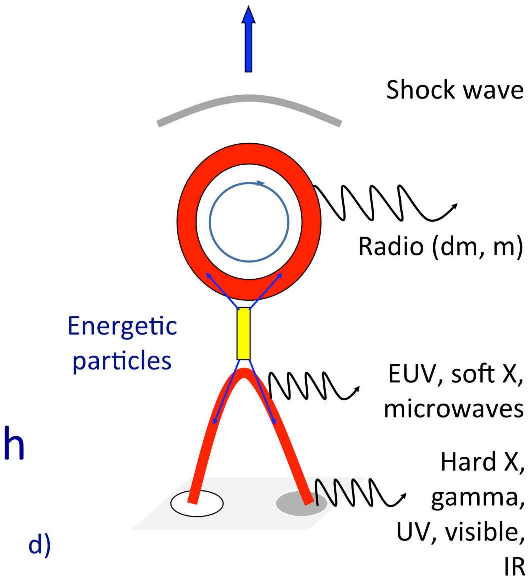
- *Left*: EUV imager (SDO/AIA):
  - erupting flux rope + "post-flare" loops
  - dimmings, EUV wave (low coronal signatures of a CME)
- *Right*: White-light coronograph (SoHO/LASCO): broad & fast CME

Eruptive solar activity associated with GLEs
Acceleration scenarios of relativistic solar particles

- Magnetic reconnection in different phases of the flare/CME development:
  - early CME development and impulsive flare phase,
  - post-CME current sheet
  - (Carmichael, 1964; Litvinenko & Somov 1995 SP 158, 317; Akimov et al. 1996 SP 166, 107; Ryan 2000 SSR 93, 581; Litvinenko 2006 AA 452, 1069; Heerikhuisen et al.; 2002 ApJ 566, 512; Chupp & Ryan 2009, Res AA 9, 11; Podgorny et al. 2010, JASTP 72, 988)



- CME shock acceleration (favoured in the contemporary literature):
  - long event duration (several days at MeV energies)
  - observation that the first relativistic protons detected at Earth are often released after the flare start
  - e.g., Gopalswamy et al. 2012 Spa Sci Rev 171, 23



Timing of energetic particle signatures in solar eruptive events: interacting electrons in the corona vs relativistic protons at 1 AU

Relative timing of GLEs and radio signatures

Relative timing with respect to coronal acceleration (electrons)

- GLE onset delayed wrt radio onset: solar cycle 23-24
  - 5-39 min (m-λ)
  - median~20 min
- (cf. also Gopalswamy et al 2012 SpaSciRev 171, 23)

Date	cm-λ	m-λ	Start GLE
1997 Nov 06	11:52-12:10	11:52-~14 UT	12:31 (+39)
2000 Jul 14	10:10 (HXR)	10:16-10:40	10:31 (+15)
2001 Apr 15	13:45	13:47-14:50	13:55 (+8)
2003 Oct 28	11:01-12:05	11:03-12:05	11:12 (+9)
2005 Jan 20	06:38-08:00	06:44-07:50	06:49 (+5)
2006 Dec 13	02:22-04:45	02:24-04:45	02:50 (+26)
2012 May 17	01:28-01:45	01:28-02:10	~01:50 (+22)
2017 Sep 10	15:52-16:50	15:50->16:40	~16:10 (+20)

- Travel time at 0.75 *c* (480 MeV) along 1.3 AU: 14.4 min (= photons + 6 min)
- Delays are generally interpreted as evidence that particles detected at 1 AU are not accelerated by the same processes/in the same regions as interacting electrons, but by CME-driven shocks

Relative timing of GLEs and radio signatures

Prompt GLE onsets

- Shortest observed delays (< 10 min) are not inconsistent with a physical relationship between the first GLE particles and the impulsive flare phase

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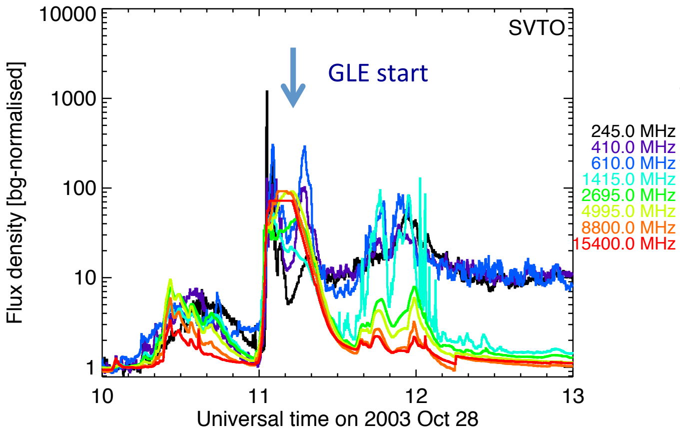
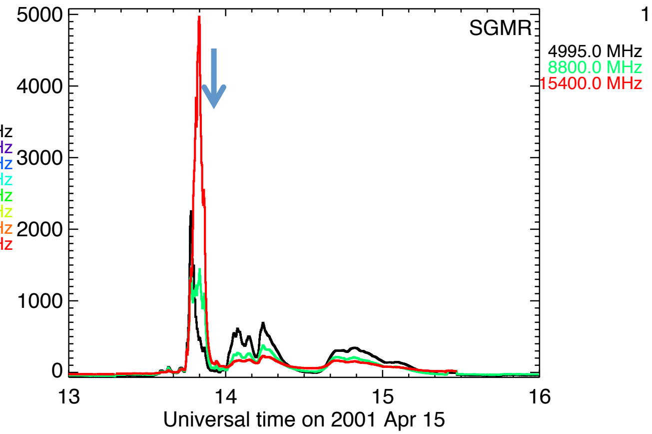
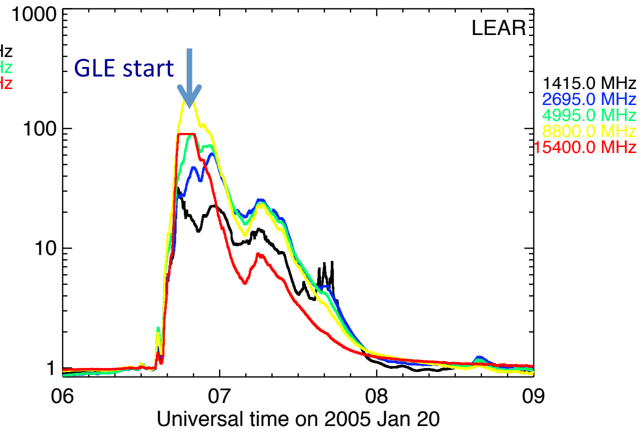
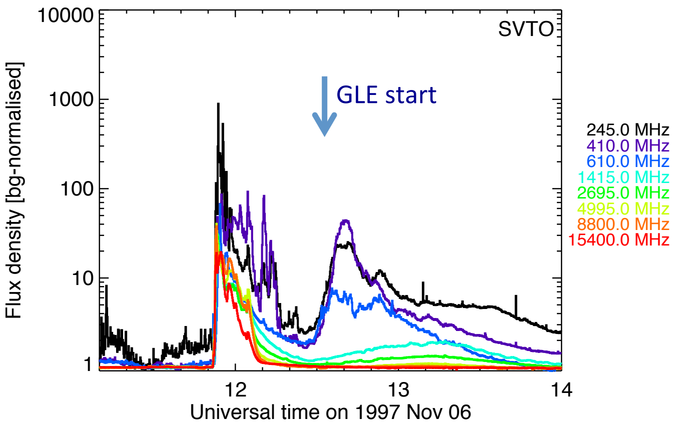






Relative timing of GLEs and radio signatures

Delayed GLE onsets



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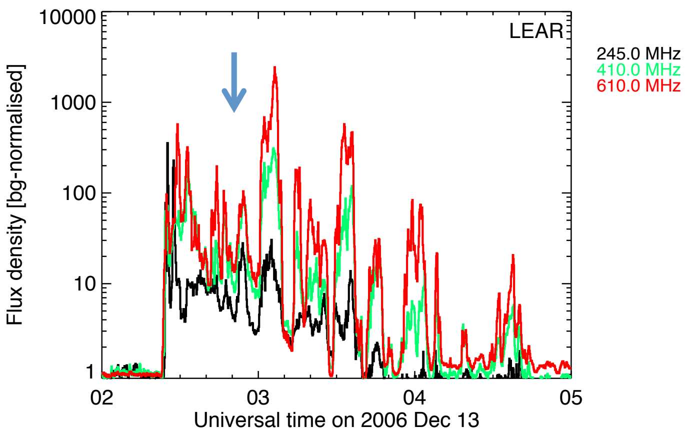

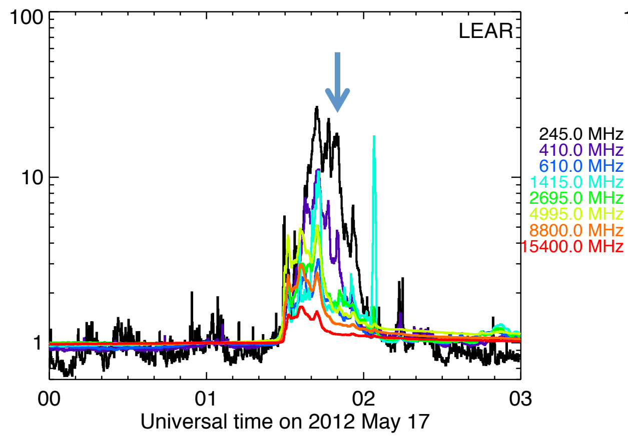

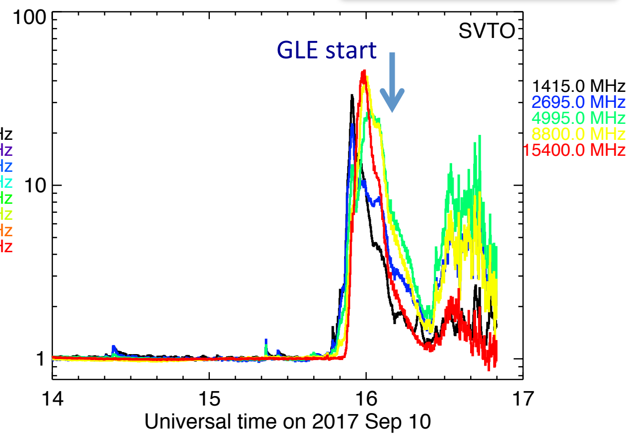

Relative timing of GLEs and radio signatures

Onset time delays of GLEs

- GLE onset delayed wrt radio onset:
  - 5-39 min (m-λ)
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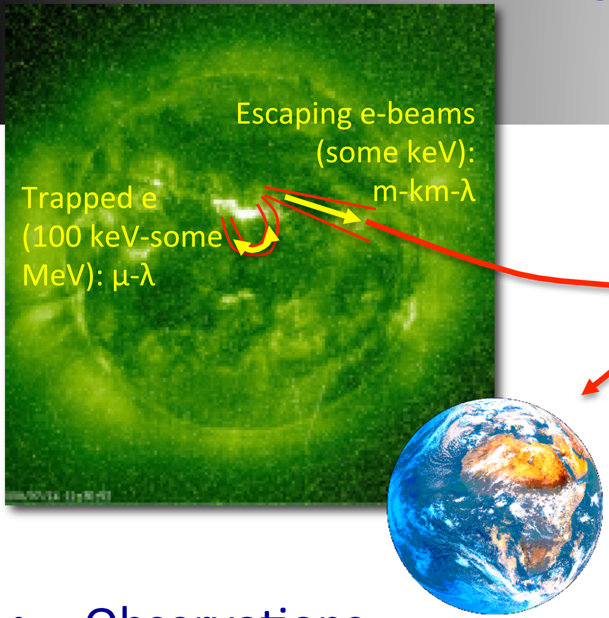
- Travel time at 0.75 *c* along 1.3 AU: 14.4 min (= photons + 6 min)
- Shortest observed delays (< 10 min) are not inconsistent with a physical relationship between the first GLE particles and the impulsive flare phase
- The longer delays are inconsistent with an impulsive phase origin, but are shorter than the overall duration of the radio emission (electron acceleration).

Prompt and delayed particle acceleration in a large relativistic SEP event

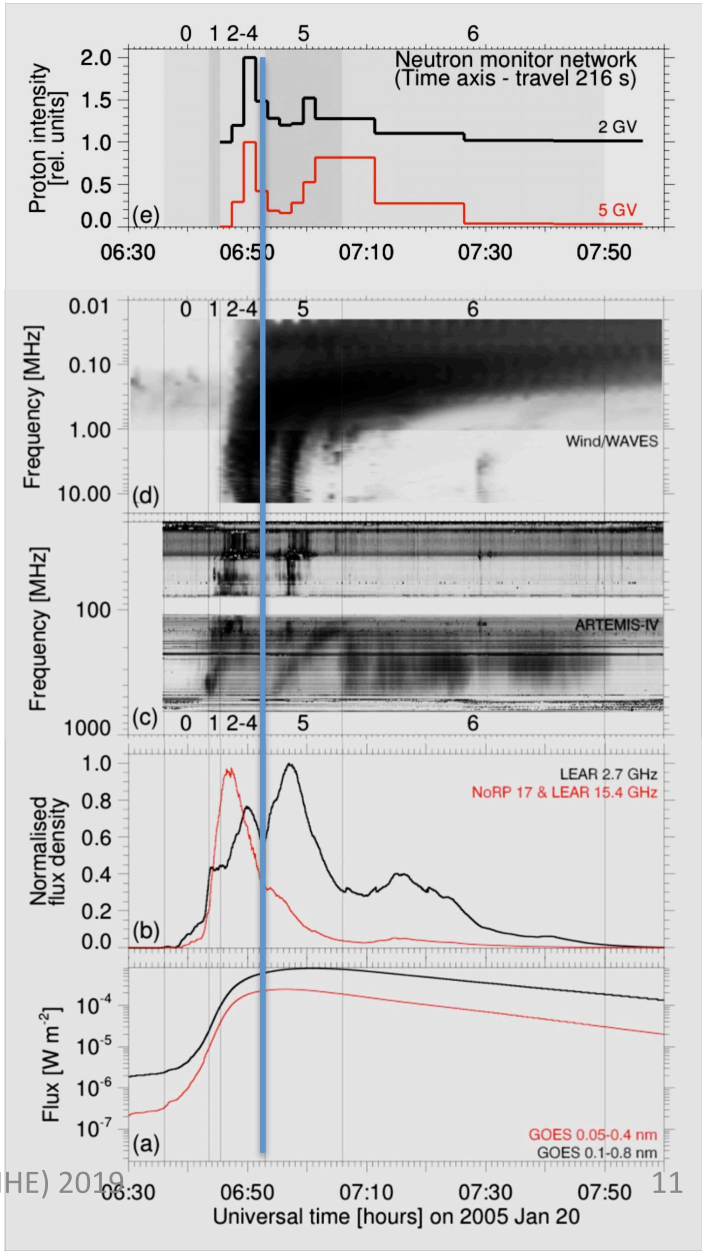
Relative timing of GLEs and radio signatures

Prompt release of relativistic protons



- Observations:
  - Early phase of GLE (first peak) in time coincidence with impulsive acceleration in the corona.
  - Open field lines flare-IP space.
  - Pion-decay photons during the impulsive flare phase (CORONAS/SONG – Masson et al. 2009)=> p>300 MeV accelerated in the flare.

- => relativistic protons at 1 AU accelerated together with interacting protons and electrons at the Sun.

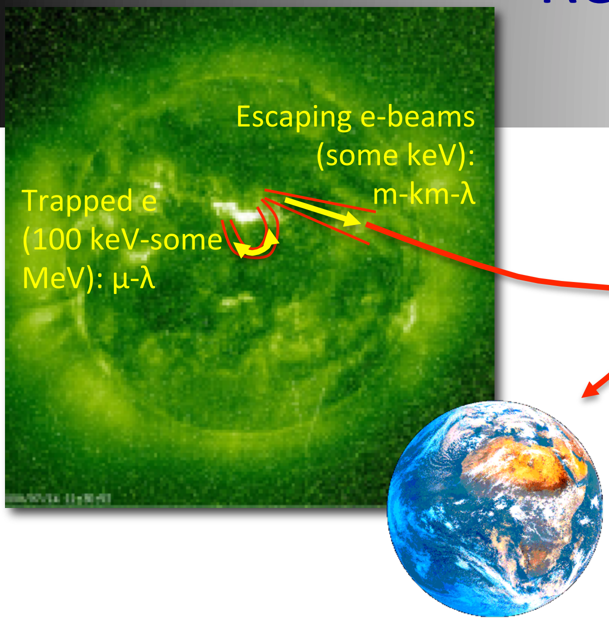


Mason et al. 2009 SP 257, 305

Klein, Masson, Bouratzis et al. 2014 AA 572, A4

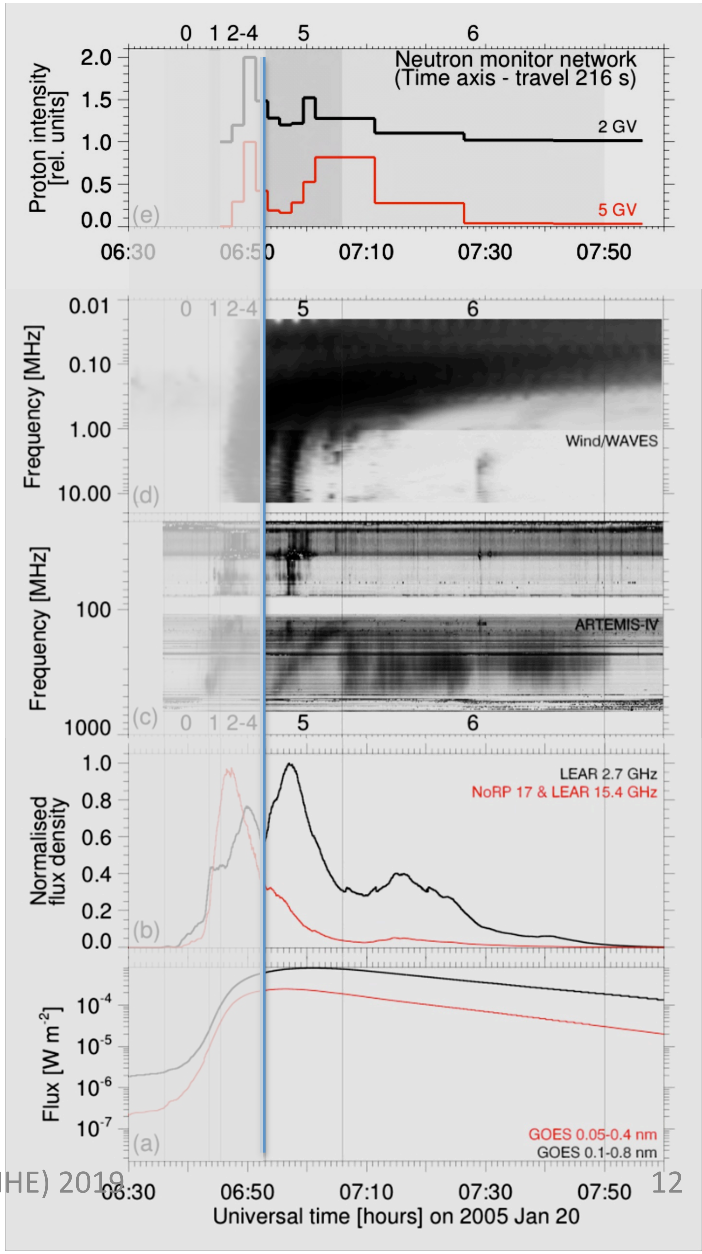
Relative timing of GLEs and radio signatures

Prompt release of relativistic protons



- Evidence that relativistic protons at 1 AU are accelerated together with interacting protons and electrons at the Sun.

- Similar timing evidence that late episodes of electron acceleration are also accompanied by the acceleration of relativistic protons reaching 1 AU ("delayed" release of relativistic protons).



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GLEs and radio bursts
Summary

- Observations of the onset of relativistic SEP events (p 450 MeV – some GeV) wrt acceleration signatures in the solar atmosphere:
  - may be delayed (5/8), but is not always
  - when delayed, GLE onsets during ongoing particle (electron) acceleration in the solar corona (radio emission)
  - on occasion (notably: 2005 Jan 20, 1997 Nov 06, 1989 Sep 29 – Klein et al. 1999 AA 348, 271), delayed GLE onsets together with distinct late episodes of particle (electron) acceleration in the corona (downstream of a rising CME).

- CME shock can explain delayed SEP acceleration, but not the timing relationships with the continuum radio emission from the corona.

- Open questions:
  - How do particles accelerated behind the CME reach open field lines (cf. Masson et al. 2013 ApJ 771, 82)?
  - How to understand the absence of prompt GLE components in GLEs where only the delayed component is seen (evolution of the magnetic connectivity in the course of an eruptive flare?)