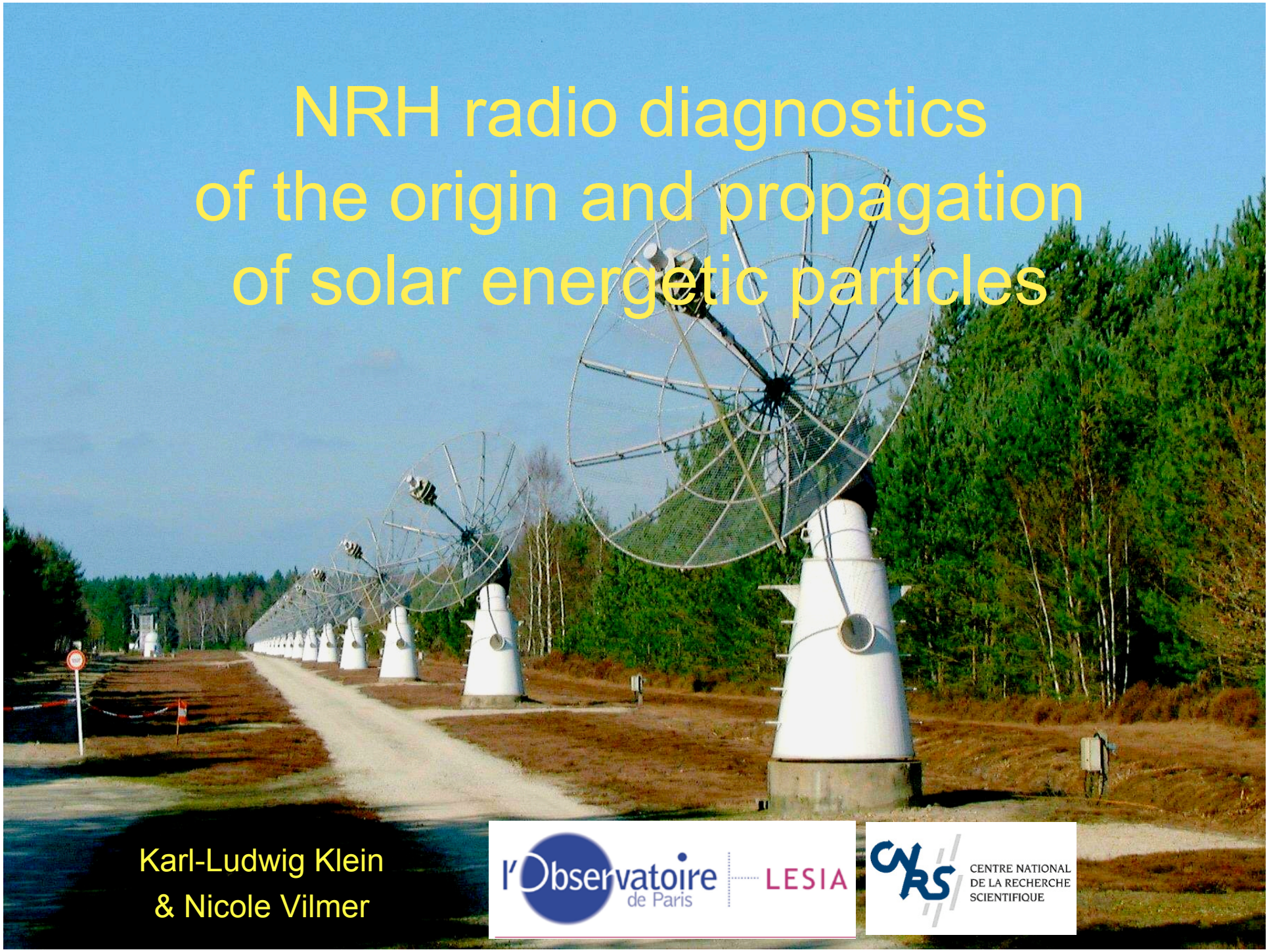
NRH radio diagnostics of the origin and propagation of solar energetic particles



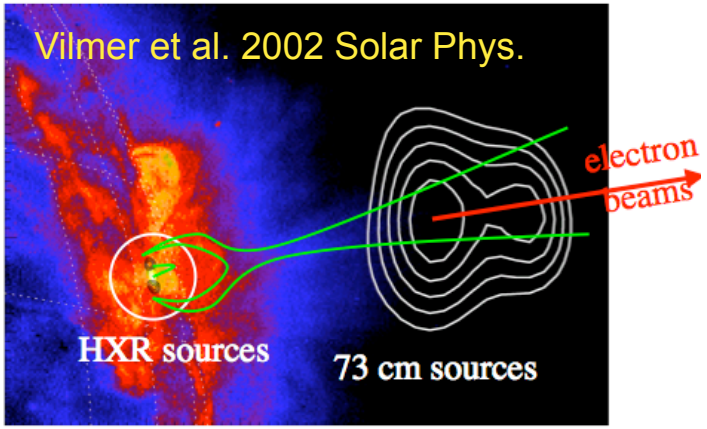
Karl-Ludwig Klein
& Nicole Vilmer

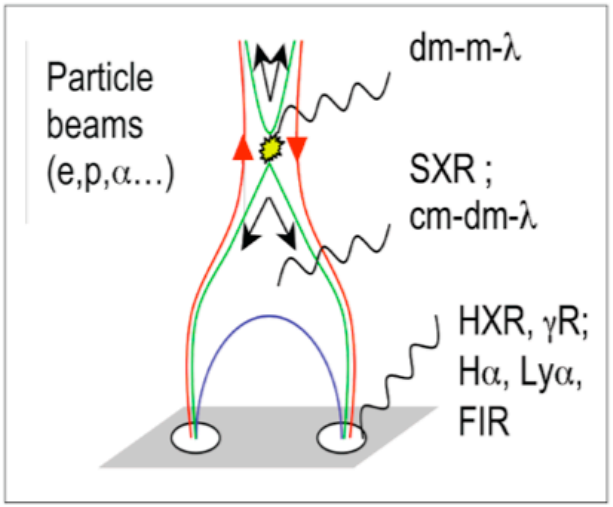
l'Observatoire de Paris | LESIA

CNRS CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

Outline

- Type III bursts as tracers of SEP propagation
  - Magnetic Sun-Earth connection in longitude & latitude
  - IP propagation channels and coronal acceleration regions
- Flares and SEP: the role of magnetic confinement
- Radio evidence of particle acceleration in large SEP events
  - Complex impulsive phase acceleration: relativistic protons at 1 AU
  - Time-extended electron acceleration: near-relativistic electrons at 1 AU



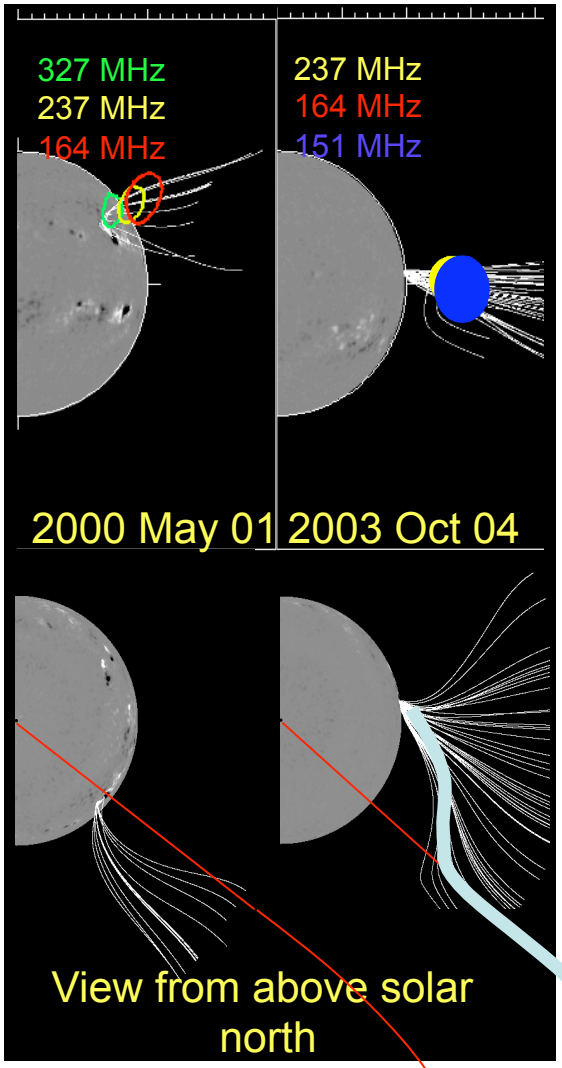


Type III bursts as tracers of SEP propagation: heliolongitude

- Coronal magnetic field configuration in flares associated with two impulsive SEP events
  - Top: extrapolated open *B* field + FWHM contours of type III radio sources (Nançay RH)
  - Bottom: view of the same field lines, from above solar north pole

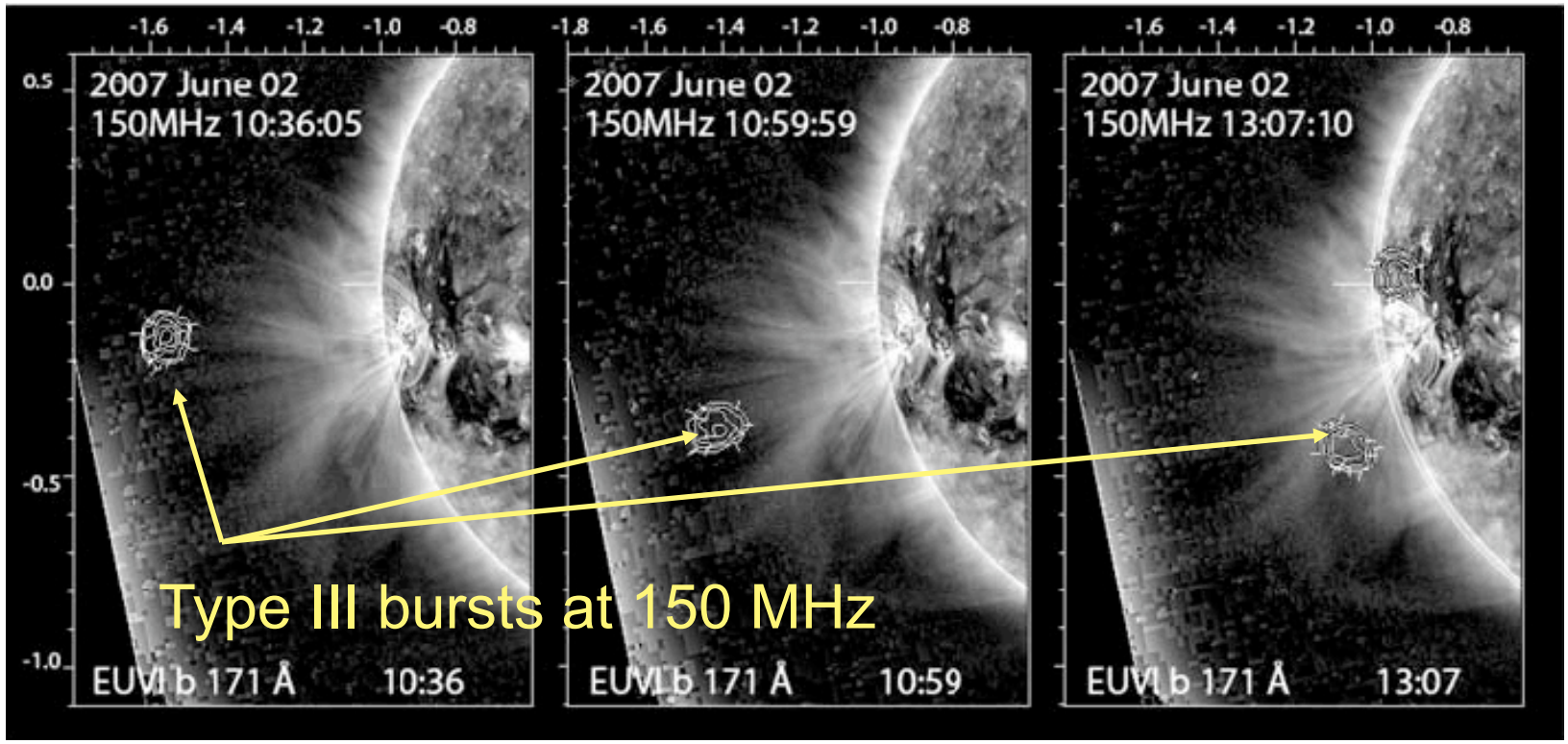
⇒ Connection in *longitude* from the AR to the Parker spiral at source surface - even when AR far (up to 40° in our sample) from nominal longitude !

⇒ Explains why we observe a large range of well-connected heliolongitudes in W hemisphere.



Klein, Krucker, Lointier, Kerdraon 2008, A&A 486, 589

Type III bursts as tracers of SEP propagation: new results with STEREO+NRH

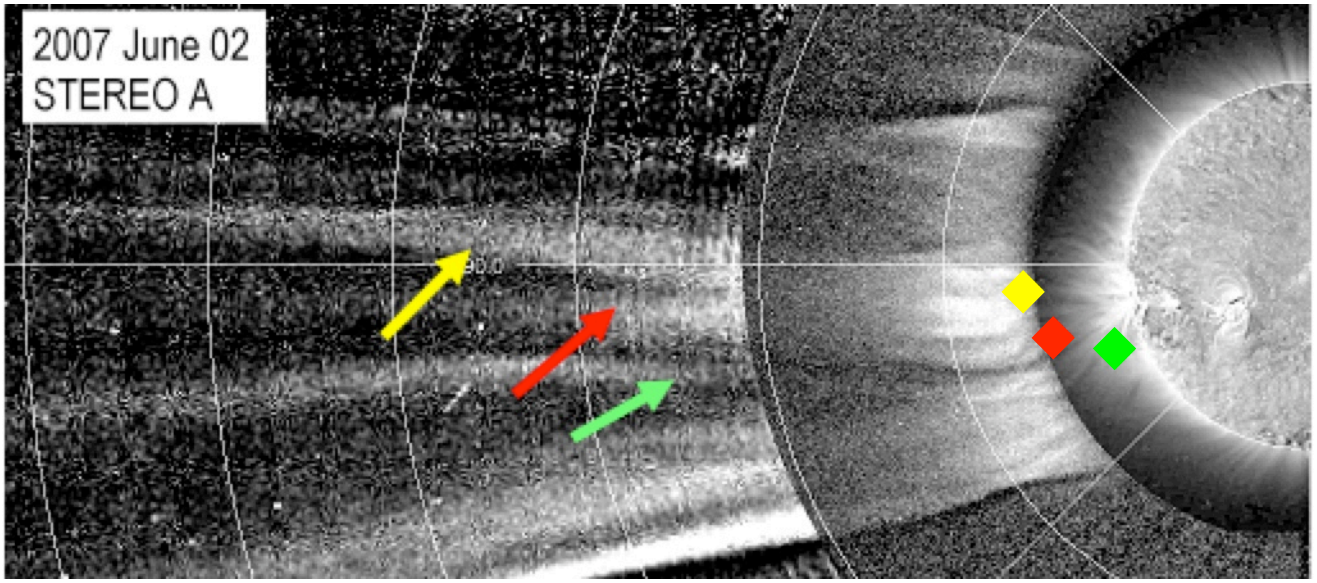


- Confirmation of e^- beams in strongly diverging coronal flux tubes (EUV)
- Successive injections into different subsets of field lines

Pick, Kerdraon, Auchère et al. 2009, Solar Phys. 256, 101

Type III bursts as tracers of SEP propagation: new results with STEREO+NRH

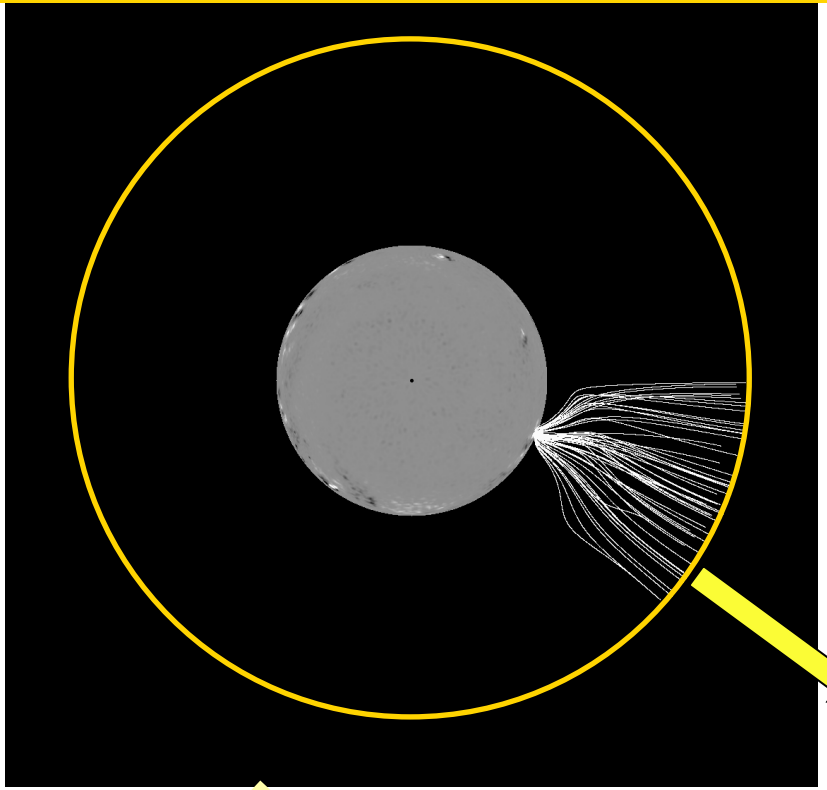
- STEREO/SECCHI + NRH:



- Confirmation of e^- beams in strongly diverging coronal flux tubes (EUV+white light)
- Successive injections into different subsets of field lines
- Extended range of heliolatitudes above source surface

Pick, Kerdraon, Auchère et al. 2009, Solar Phys. 256, 101

Type III bursts as tracers of SEP propagation: IP flux tubes and coronal acceleration regions



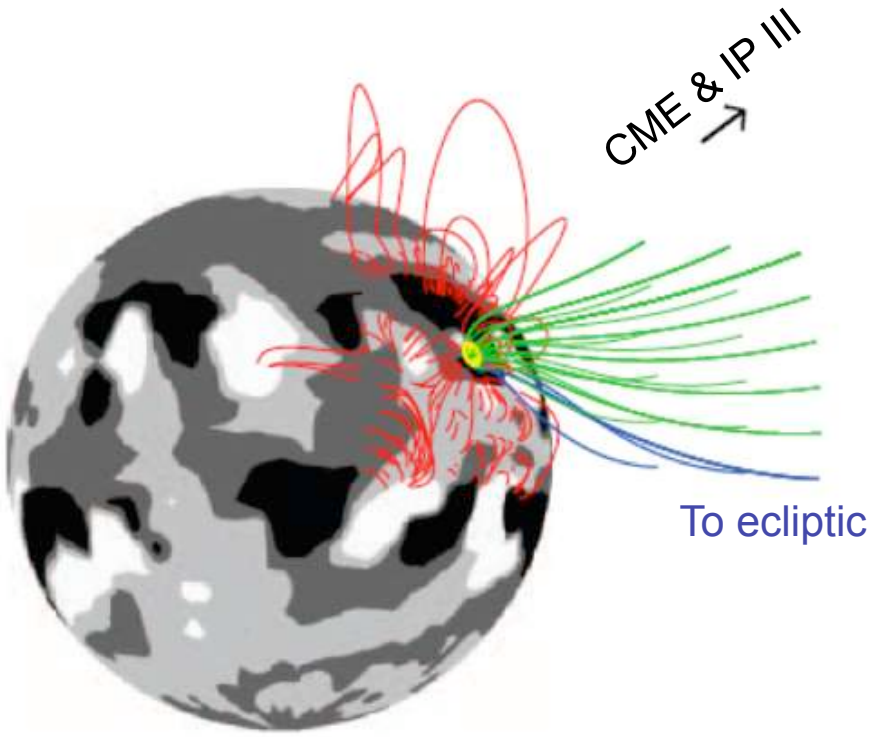
- When observed in situ, impulsive SEP propagate in narrow flux tubes; at 1 AU : Ø=6×10^6 km (keV e^- Buttighoffer 1998 A&A 335, 295; MeV/n ions Mazur et al 2000 ApJ 532, L79)
- Cross section << open flux tubes at source surface inferred from PFSS; subset of open field lines.

Ø=6×10^6 km

- Cross section in the low solar atmosphere: a few 10^3 km
- consistent with small-scale acceleration regions in flares.

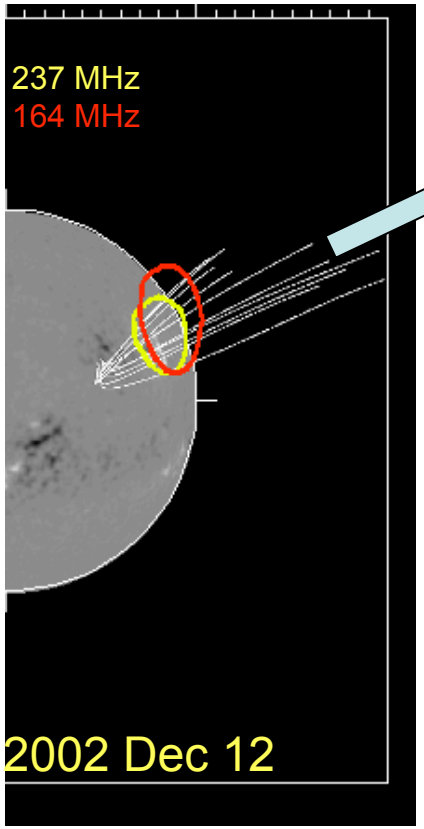
Type III bursts as tracers of SEP propagation: heliolatitude

- Particles from flares at high heliolatitudes: how can they be detected in the ecliptic plane near 1 AU ?
  - One interpretation: PFSS extrapolations fail to explain how SEP events detected at Earth can originate in high latitude AR (Nitta et al 2006 ApJ 650, 438; Rust et al 2008 ApJ 687, 635).
  - But: how realistic is the assumption that the IP magnetic field has no meridional component (following Parker) ?



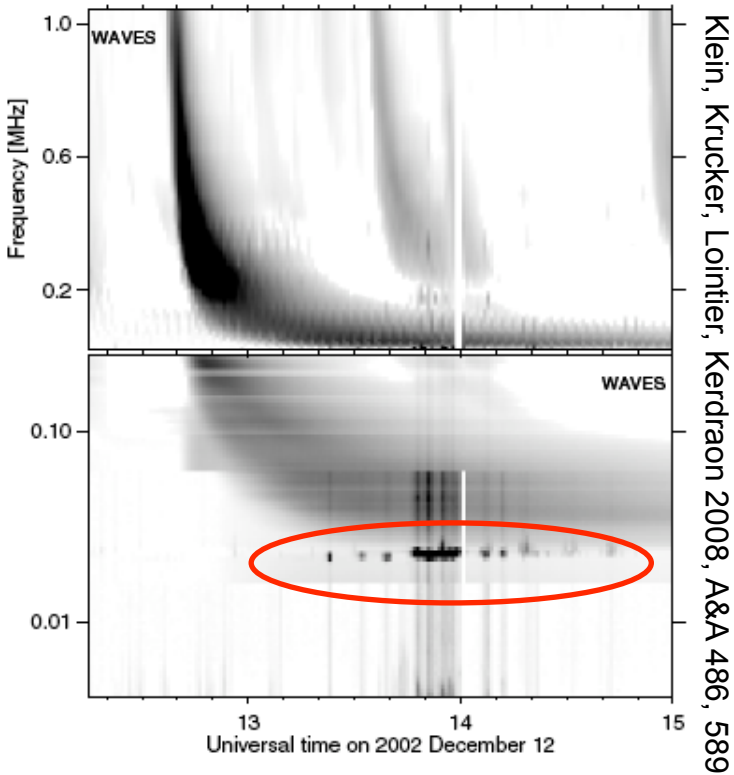
Y.-M. Wang, Pick & Mason 2006, ApJ 639, 495

Type III bursts as tracers of SEP propagation: heliolatitude



Particle propagation to high heliolatitudes in the corona (m-λ type III)

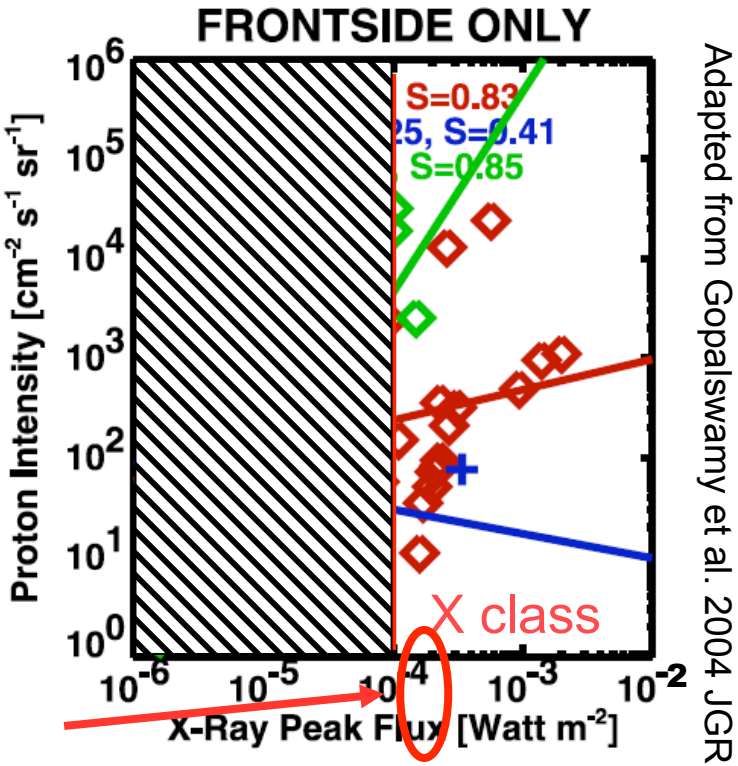
km-λ type III at s/c accompanied by Langmuir waves (e^- beam intercepted by s/c)



⇒ parent AR connected to the source surface at high latitude, but IP field lines curve down to the ecliptic before reaching 1 AU (≠ Parker).

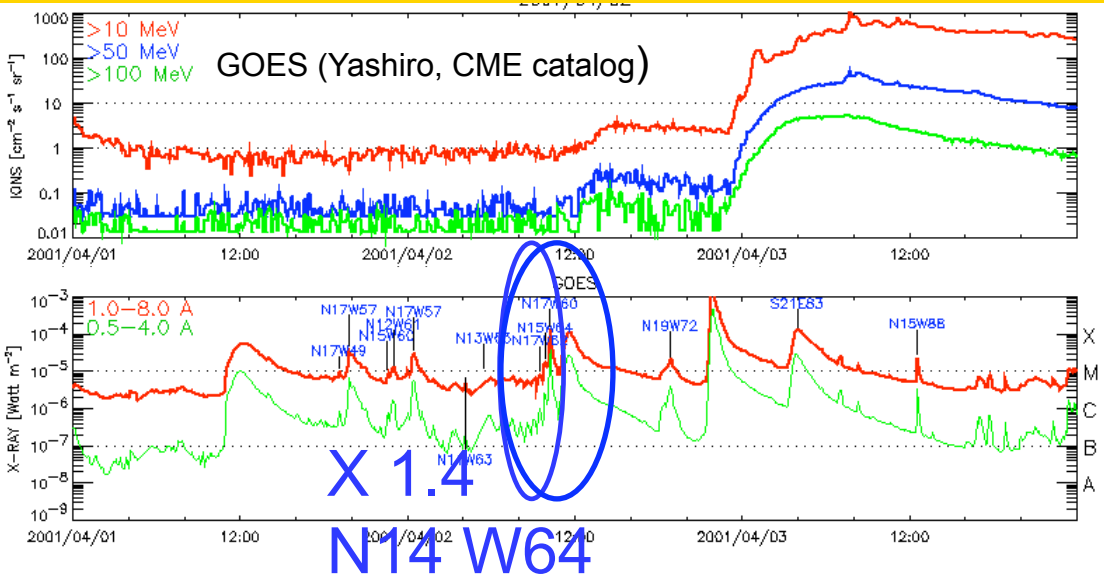
Flares and SEP: the role of magnetic confinement

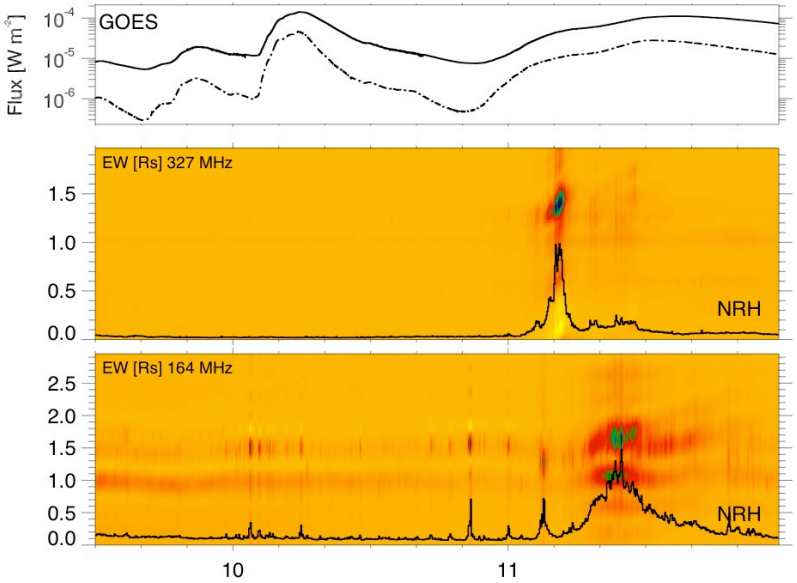
- Identify flares without CME (LASCO/SoHO or EIT/SoHO: no CME, no dimmings; Wang & Zhang 2007 ApJ 665, 1428):
  - 11/104 X-class flares without CME (1996-2004)
  - 4/11 confined flares in W solar hemisphere: none has SEP event detected by GOES; flux <1 pfu
  - Absence of particle acceleration in the corona ? Confinement of the accelerated particles ?

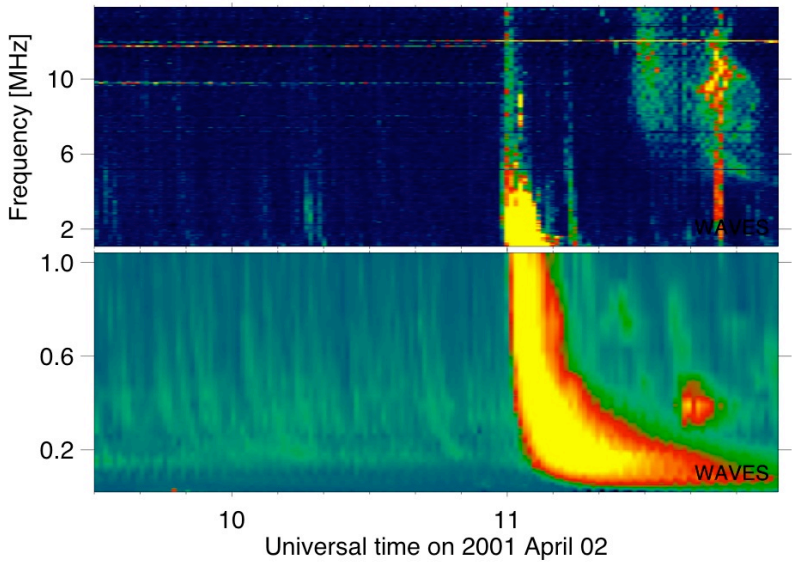


Adapted from Gopalswamy et al. 2004 JGR

Flares and SEP: the role of magnetic confinement







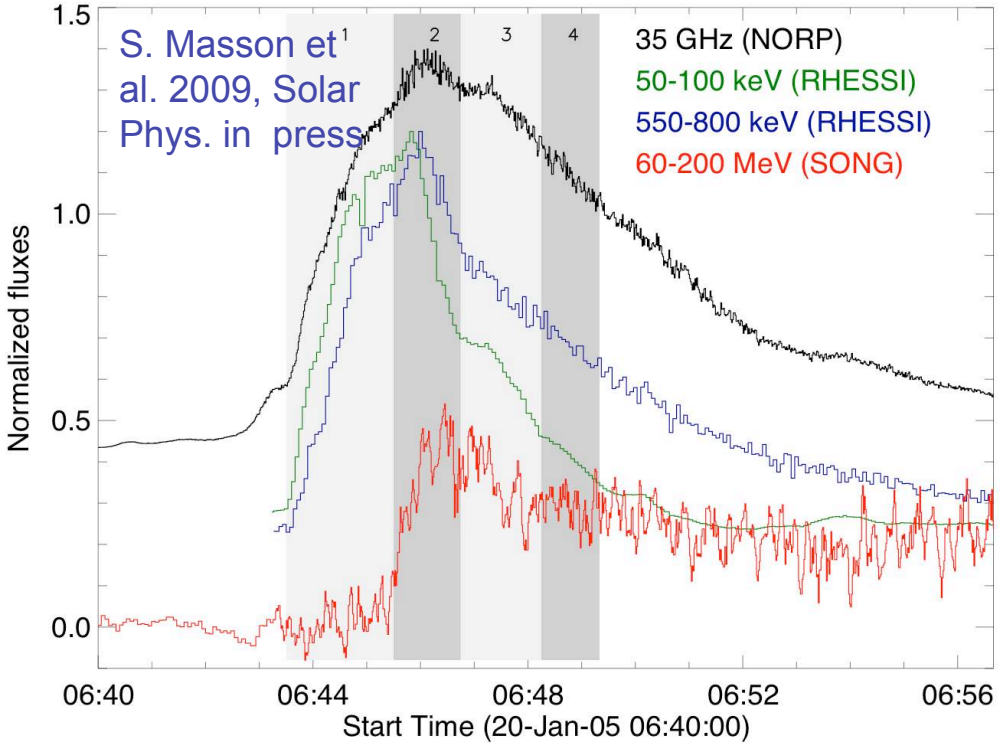
‘Confined’ flare :

- Particle acceleration in the corona (Bern: μw→50 GHz)
- no SEP
- Cutoff at dm-m-λ
- no type III (no e→IP space)

Particles remain trapped in corona.

Klein, Trottet, Vilmer 2009, ICRC Lodz

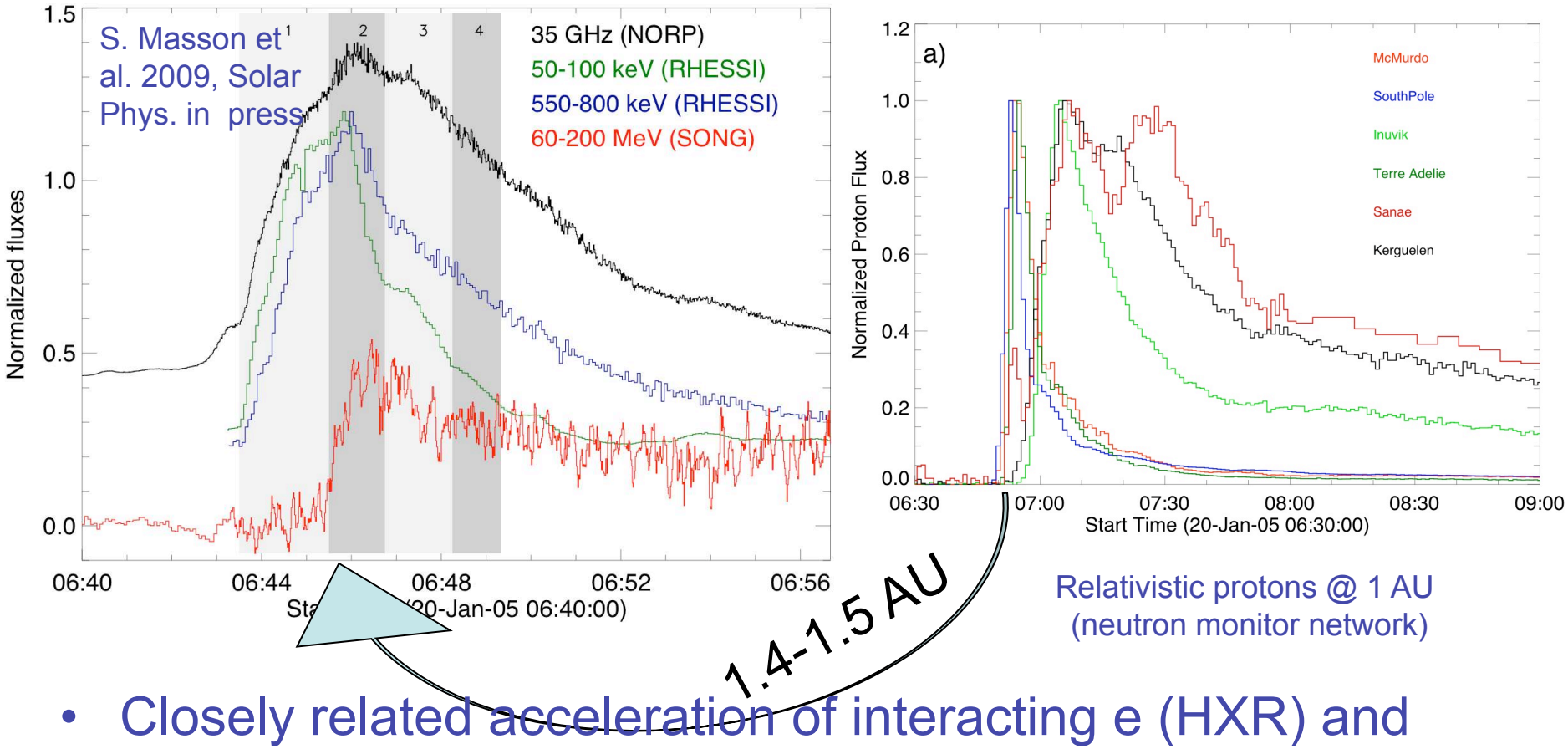
Radio evidence of particle acceleration in large SEP events: origin of relativistic protons at 1 AU



- Complex time history of flare-related particle acceleration (e, p)
- HXR sources (RHESSI): simultaneous double footpoints, rapidly varying configuration (fragmented acceleration; Krucker et al. 2008 ApJ). Reconnection in the corona.

- Closely related acceleration of interacting e (HXR) and relativistic p (gamma $h\nu$>60 MeV; delay w/r onset !)

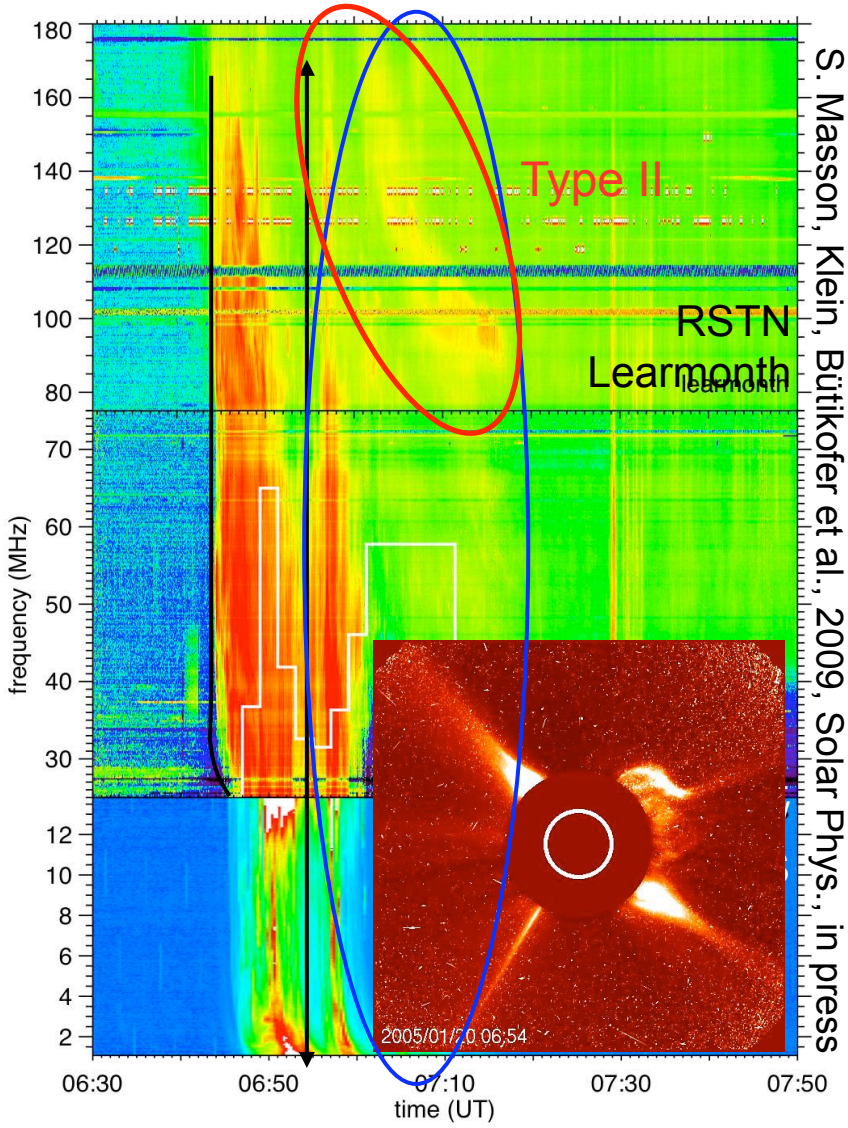
Radio evidence of particle acceleration in large SEP events: origin of relativistic protons at 1 AU



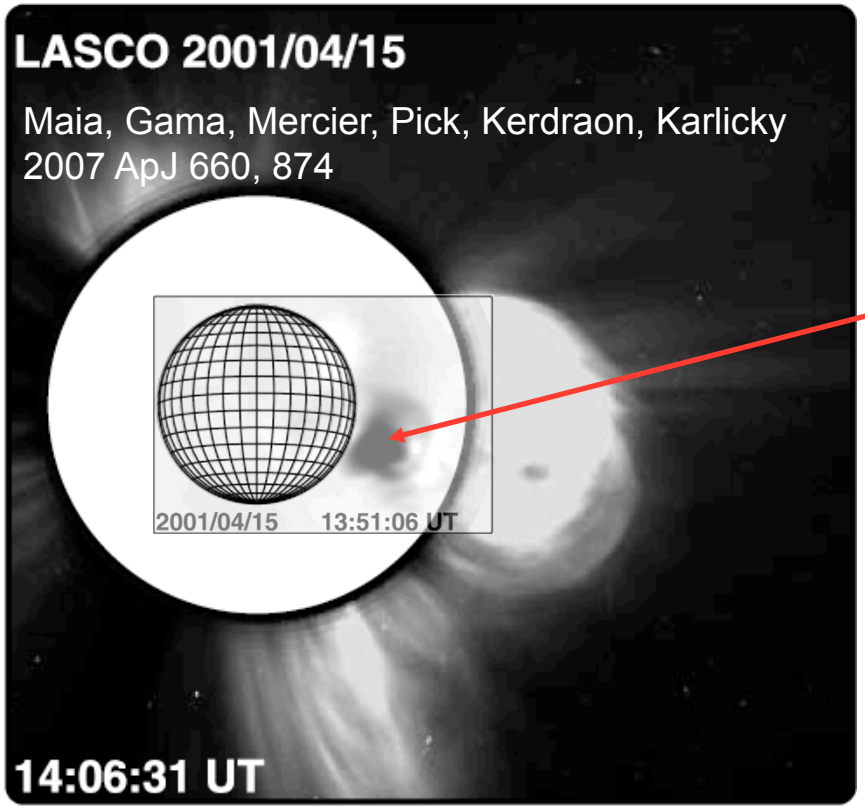
- Closely related acceleration of interacting e (HXR) and relativistic p (gamma $h\nu$>60 MeV; delay w/r onset !)
- Closely related acceleration of interacting *and escaping* relativistic p

Radio evidence of particle acceleration in large SEP events: origin of relativistic protons at 1 AU

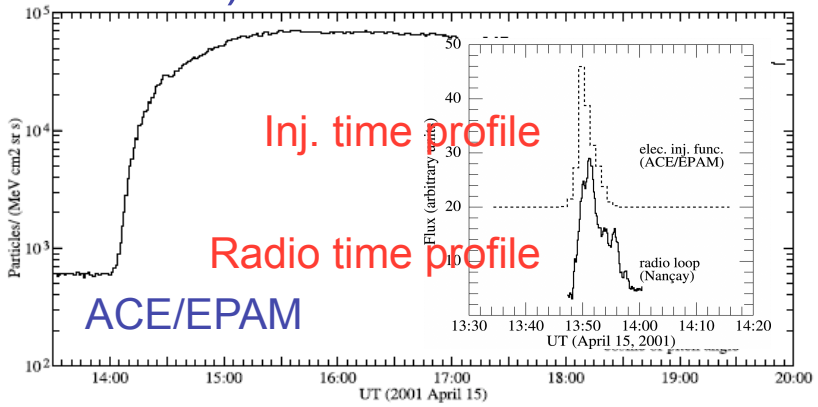
- First relativistic p seen at Earth accelerated with interacting particles
- Acceleration after flare start; first accelerated e do NOT escape
- 2nd peak of relativistic p with new m-Dm-λ type III, m-λ type II (shock wave), and synchrotron emission
- Origin of type II: behind CME (Pohjolainen et al. 2007 SP 244, 167)
- Imaging needed over an extended ν-range !



Radio evidence of particle acceleration in large SEP events: origin of relativistic electrons at 1 AU



- SoHO/LASCO : fast CME
- Nançay RH : synchrotron emission from relativistic electrons (behind CME front when bwd extrapolated; acceleration in the perturbed corona).



- Particle acceleration in the magnetically stressed corona in the aftermath of a CME.

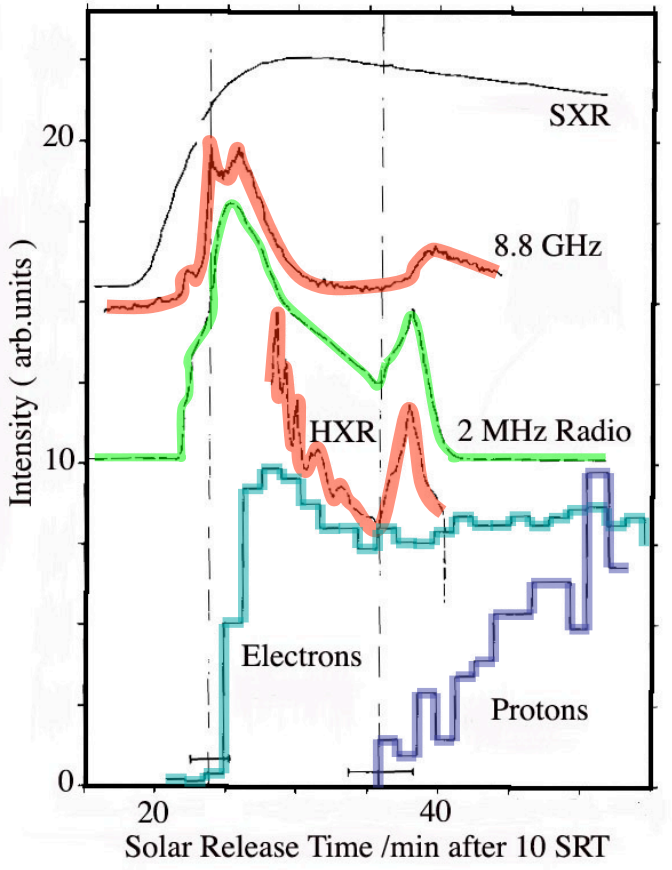
⇐

- + transport modelling (adiabatic focussing + PA scattering)

(see also Akimov et al. 1996 SP 166, 107; Klein et al 1999 AA 348, 271; Laitinen et al 2000 AA 360, 729; Klein & Trottet 2001, Spa Sci Rev 95, 215).

Conclusion

- Imaging + spectrography at dm-m-λ provide unique information on SEP acceleration, escape, propagation.
- Key topic of solar & solar-terrestrial physics in the coming years: *Investigate the links between the solar surface, corona and inner heliosphere - What are the solar sources, acceleration and transport processes of energetic particles ?*
  - *Solar Orbiter*: HXR imager + radio spectro + energetic particle detector.
  - Radio spectral imaging at dm-m-λ (+ long m-λ) to optimise the scientific return of *Solar Orbiter, Solar Probe*+ or any other project that addresses the above key question: FASR, NRH+



Kallenrode & Wibberenz
1991 ApJ 376, 787