Understanding the Sun via gamma-ray lines

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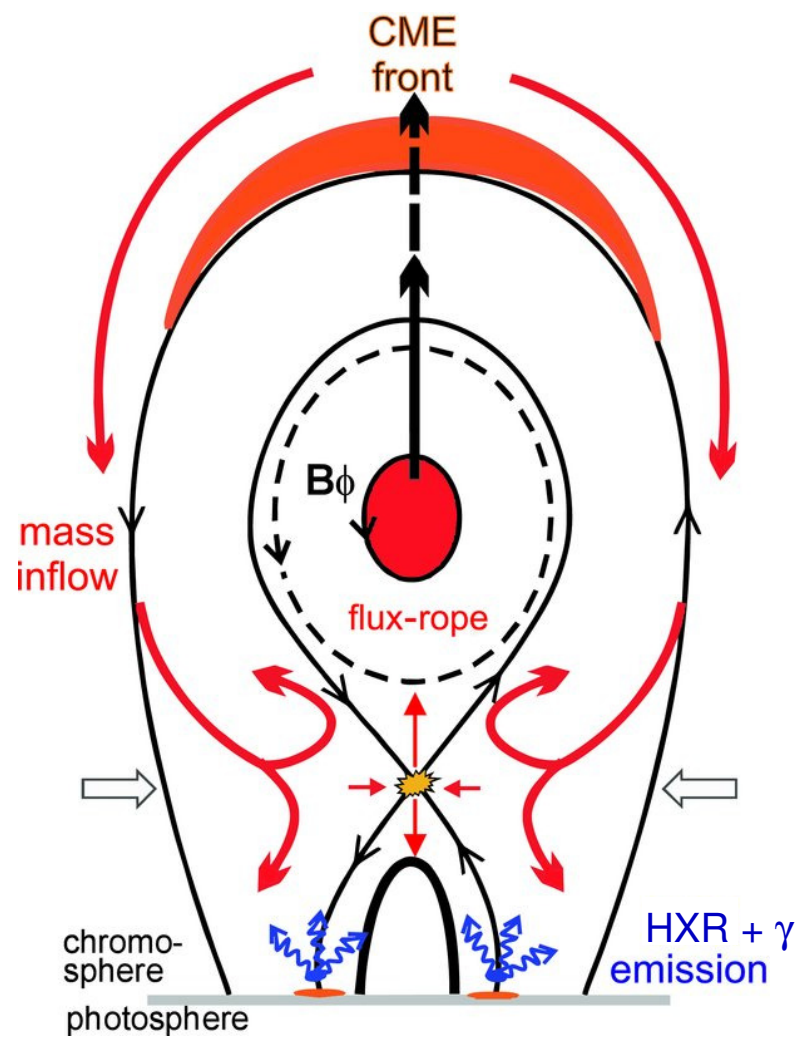
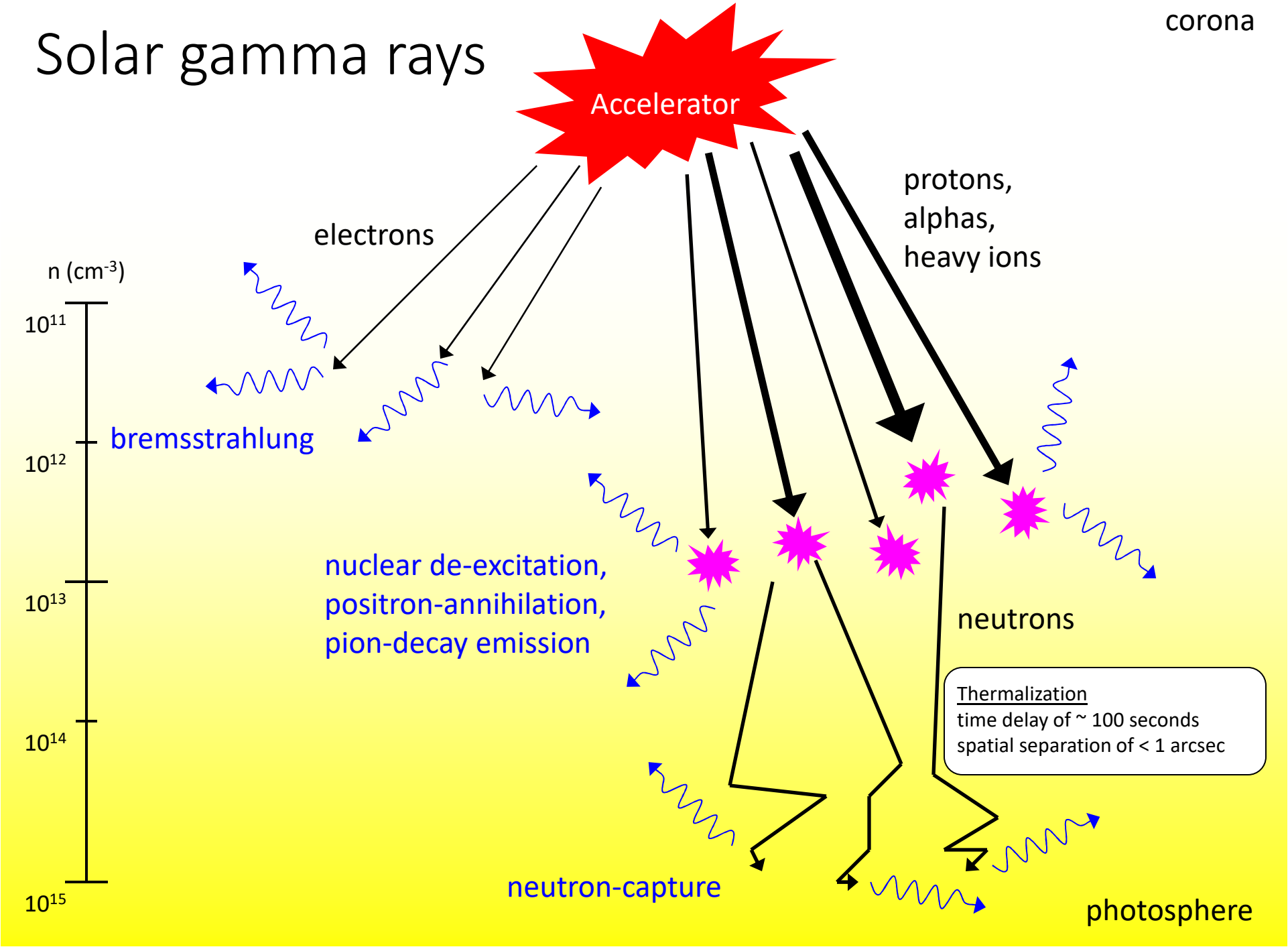
Solar ion acceleration

- Solar eruptive events (SEEs) accelerate both ions and electrons
  - Both flares and CMEs accelerate particles
  - Particle acceleration is efficient: up to tens of percent of the released magnetic energy
- Accelerated ions can be characterized through the gamma rays they produce (see next slide)
  - Compact sources associated with flare loops
  - Diffuse source from particle precipitation



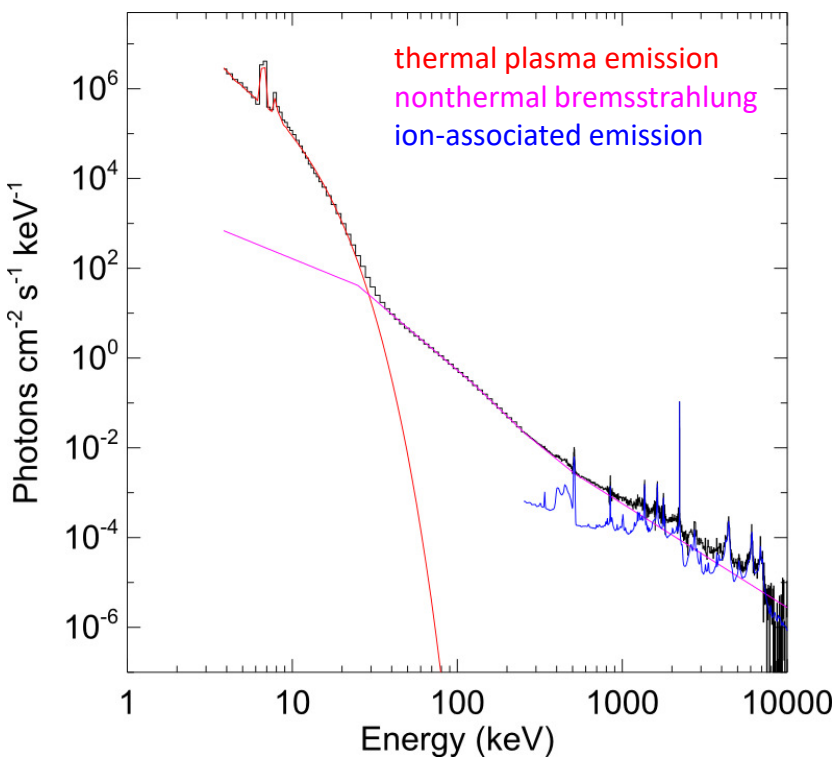
(modified from Temmer et al. 2010)

Solar gamma rays



≲10 MeV spectroscopy

Composite *RHESSI* spectrum for 2002 July 23 X4.8 flare



(Lin 2011)

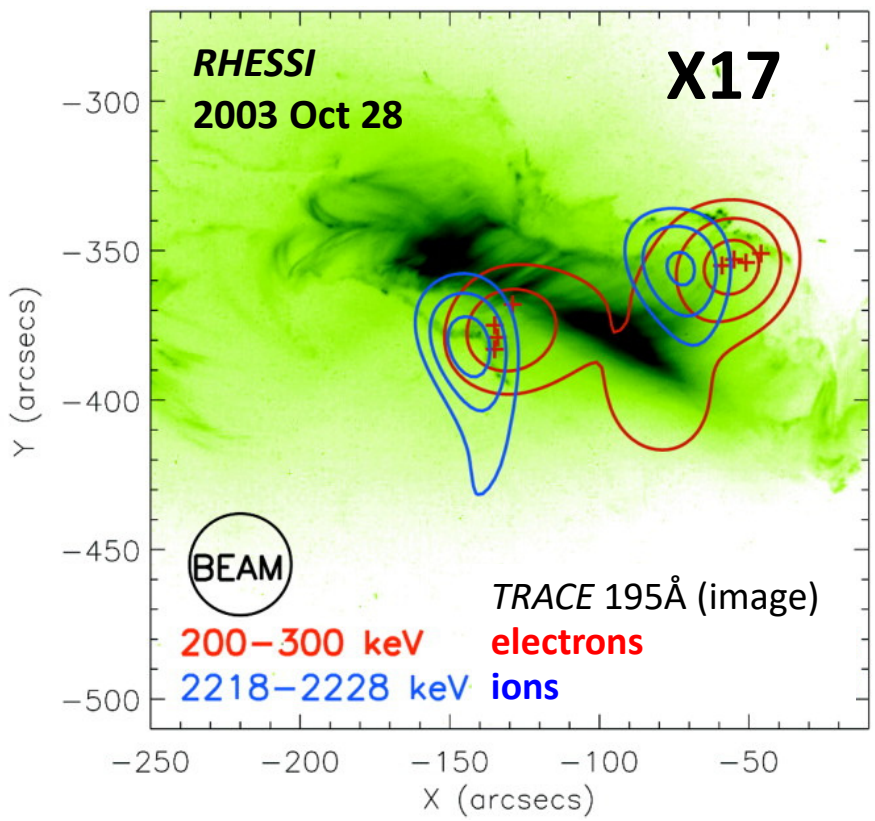
- Thermal plasma emission
  - Plasma temperature
  - Plasma abundances
- Relativistic bremsstrahlung continuum from electrons
  - Electron energy spectrum
  - Electron angular distribution
- Nuclear de-excitation lines
  - Ambient abundances
  - Accelerated abundances
  - Ion energy spectrum (~3–10 MeV/nuc)
  - Ion angular distribution
- Neutron-capture line (2.223 MeV)
  - Accelerated ions (~20 MeV/nuc)
- Positron-annihilation line (511 keV)
  - Ambient conditions such as temperature

Instruments for gamma-ray lines

- *SMM*/GRS (spectroscopy)
  - NaI scintillators → a few % FWHM
- *RHESSI* (spectroscopy and imaging)
  - HPGe detectors → <1 % FWHM
  - Fourier-transform imaging via tungsten bi-grid collimators → 35 arcsec angular resolution
- *Fermi*/GBM (spectroscopy)
  - NaI and BGO scintillators

Where are ions accelerated?

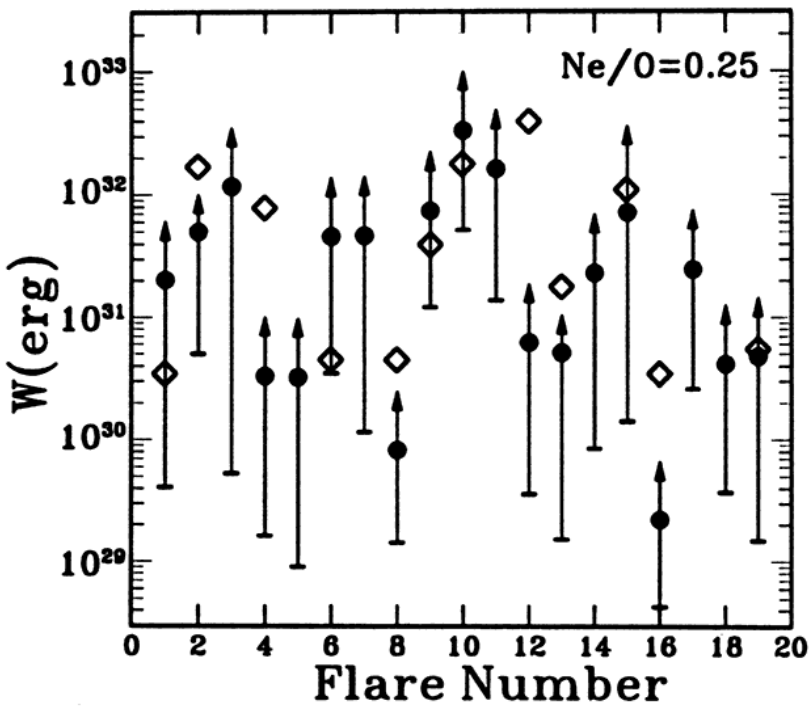
- *RHESSI* imaged flare footpoints for a gamma-ray line (2.2 MeV neutron-capture line)
- These compact sources contain all of the spectroscopically observed 2.2 MeV line flux
  - ~20 MeV/nuc ions confined to flare loops
  - ~20 MeV/nuc ions not precipitating from the CME shock
- Offset between ion footpoints and electron footpoints indicate differences in acceleration/transport



(Hurford et al. 2006)

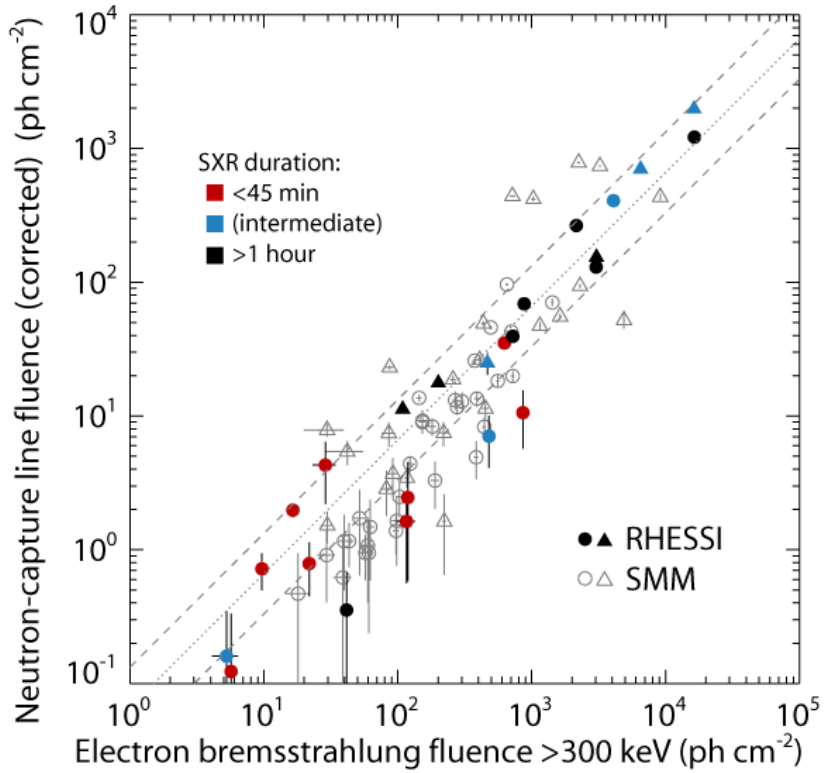
How is ion acceleration coupled to electron acceleration?

Similar energy content in ions (●) and electrons (◇) as observed by *SMM*/GRS



(Ramaty et al. 2000)

Proportional acceleration of ~20 MeV/nuc ions and >300 keV electrons

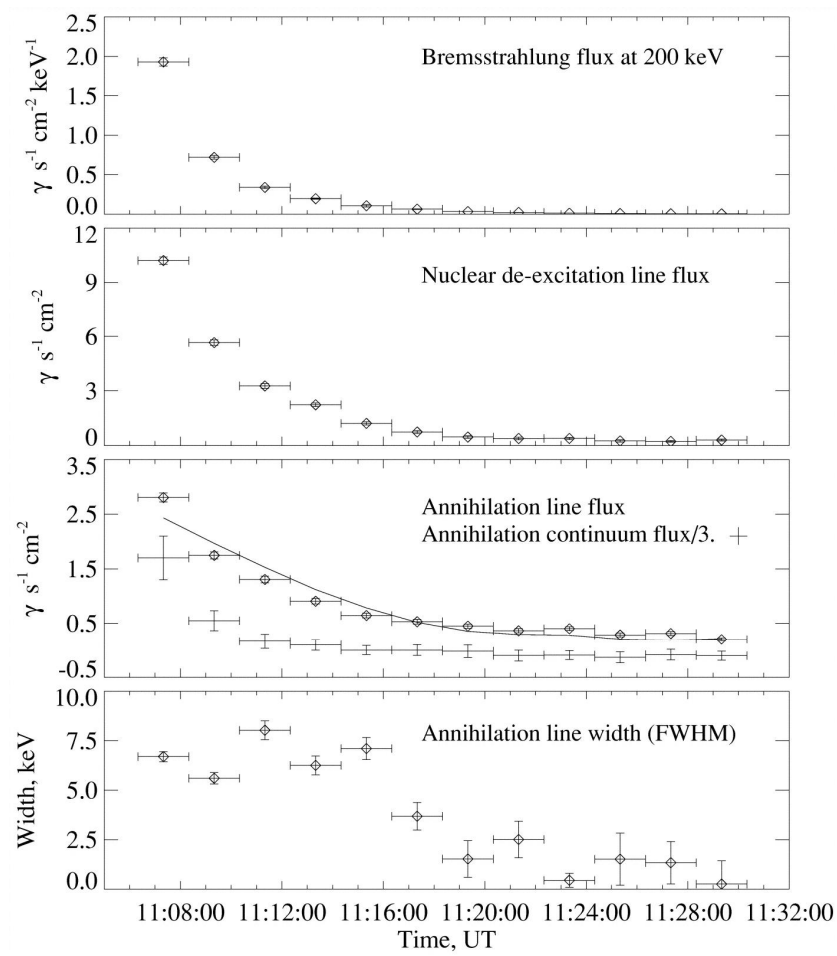


(Shih et al. 2009)

Where does the energy in ions get deposited?

- The positron-annihilation line narrowing in a flare indicates changes in interaction region
  - Broad line: density of ~10^{14}–10^{15} cm^{-3} at ~10^5 K
  - Narrow line: density of ≥10^{15} cm^{-3} at <10^4 K, still ionized
- A couple of flares have shown ambient abundances that evolve from photospheric-like to coronal-like (not shown)

RHESSI spectroscopy for 2003 Oct 28 X10 flare



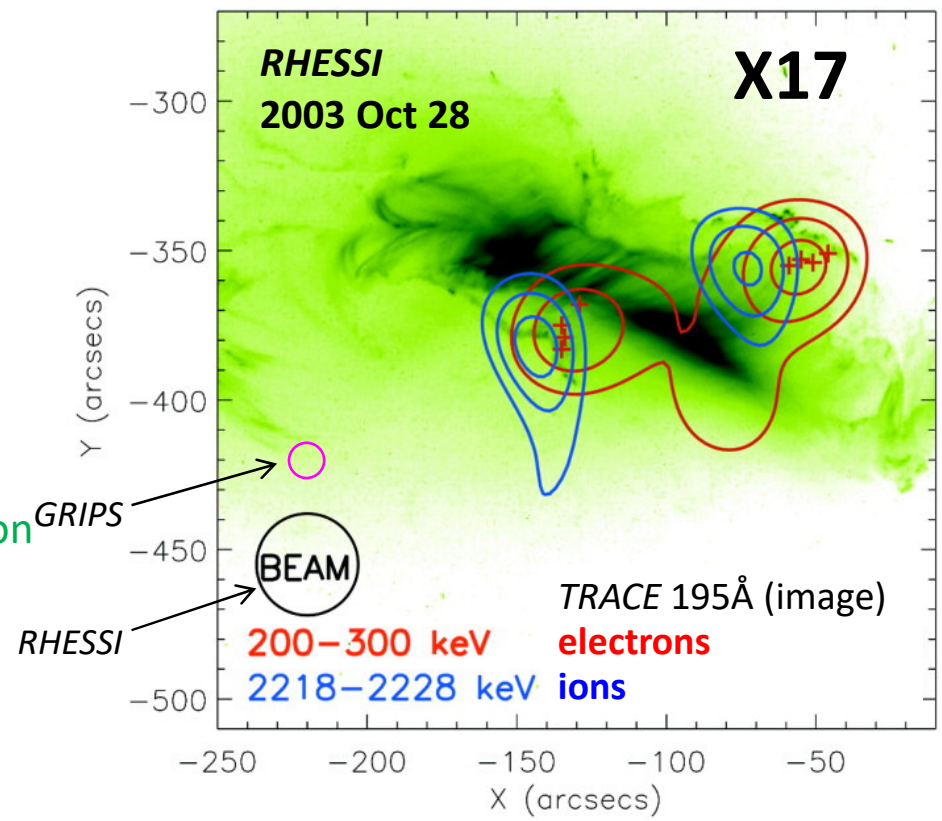
(Share et al. 2004)

Future needs for solar gamma-ray measurements

- Any observations whatsoever!
  - Ions contain ~half of the energy released into particles
  - Ions may have a significant role in flare heating
- High angular resolution and high image quality
  - Ion acceleration/transport versus electron acceleration/transport
- High sensitivity
  - Evolution in large flares
  - Small flares
  - Signatures of sub-MeV ions

Gamma-Ray Imager/Polarimeter for Solar flares (*GRIPS*)

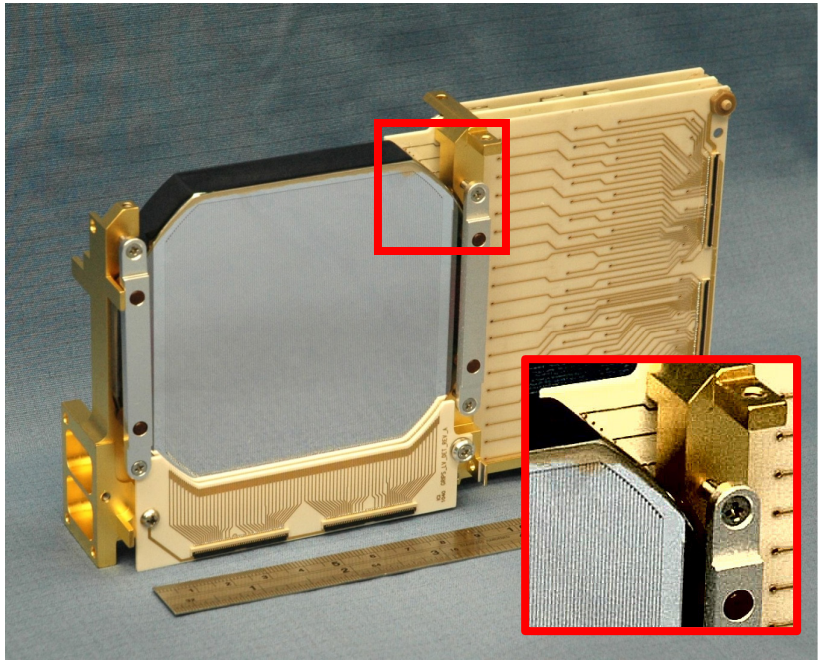
- Balloon mission funded under the NASA Heliophysics LCAS program
- PI: Pascal Saint-Hilaire (UC Berkeley)
- Capabilities
  - <1% FWHM spectral resolution
  - 12.5 arcsec angular resolution with high image quality
- Implementation
  - HPGe detectors with 3D position sensitivity
  - Coded aperture is a grid of tungsten-copper slats
  - 8-meter grid-spectrometer separation



(Hurford et al. 2006)

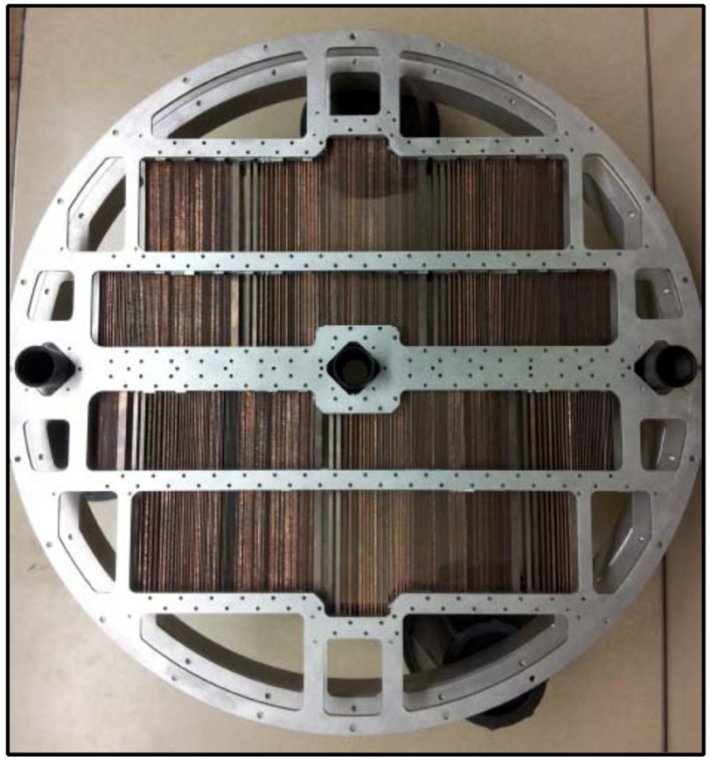
GRIPS implementation

3D position-sensitive HPGe detectors (3D-GeDs)



7.5cm × 7.5cm × 1.5cm detectors
149 strips on each face (0.5-mm pitch)

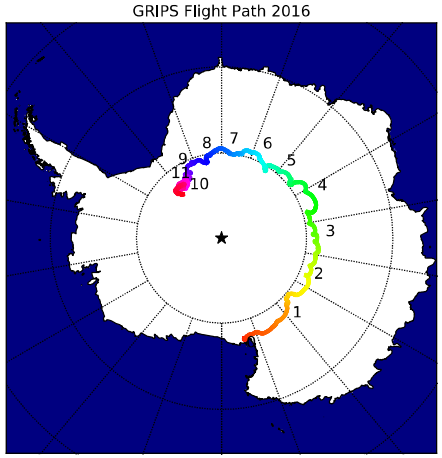
Multi-pitch rotating modulator (MPRM)



W/Cu slit/slat pitch ranges from 1 to 13 mm
MPRM rotates at 10 rpm

GRIPS status

- *GRIPS* has had one Antarctic flight
  - ~10^6 seconds in January 2016
  - The Sun produced 21 small (C-class) flares, with no appreciable gamma rays
- *GRIPS* recently funded for a second Antarctic flight
  - Instrument needs to be rebuilt following recovery



The *GRIPS* field team in front of the instrument

Compton Spectrometer and Imager (*COSI*) SMEX

- Astrophysics SMEX mission undergoing a Phase A study
- PI: John Tomsick (UC Berkeley)
- Capabilities
  - <1% FWHM spectral resolution
  - Compton-imaging angular resolution usable for background rejection
- Implementation
  - *GRIPS*-like HPGe detectors with 3D position sensitivity
- High-energy astrophysics missions can make groundbreaking measurements of the Sun: most recently, *Fermi* and *NuSTAR*
- Two COSI talks on June 9
  - 12:30pm, 309.04: "The Compton Spectrometer And Imager: Audacious Advancements In Mev Astronomy" by Terri Brandt
  - 4:50pm, 324.05: "COSI: From Data to Images and Spectra" by Andreas Zoglauer

Solar Maximum Energetic Ion induced Gamma Ray Line Spectrometer (*SMEIGLS*)

- ISS-borne instrument proposal pending selection under the Heliophysics FORT program
- PI: Lee Mitchell (NRL)
- Capabilities
  - High effective area
- Implementation
  - Compact array of bright scintillators

Instrument	511 keV		2.2 MeV	
	$Area_{pp}$	FWHM	$Area_{pp}$	FWHM
SMEIGLS	268 cm^2	24 keV	135 cm^2	49 keV
Fermi/GBM	120 cm^2	70 keV	40 cm^2	150 keV
RHESSI	27 cm^2	2 keV	19 cm^2	4 keV
SMM/GRS	175 cm^2	41 keV	66 cm^2	85 keV

Additional possibilities

- Other astrophysics gamma-ray missions
- Space-borne version of *GRIPS*
  - ~5 arcsec angular resolution
- Direct gamma-ray imaging, although with FOV concerns
  - Fresnel lenses
  - Laue lenses
- The next Heliophysics Decadal Survey is around the corner!
  - The previous Decadal Survey studied the Solar Eruptive Events (SEE) 2020 mission concept, which included a gamma-ray instrument

Summary

- Solar gamma-ray lines (~0.5–10 MeV) are vital for understanding:
  - Ion acceleration at the Sun
  - Energy transport into the chromosphere
- We aspire for improved observations!
  - Platform: balloons to orbital spacecraft
  - Solar science: primary to ancillary
- See also the poster right now, 127.05: “New Solar-Flare Particle Acceleration And Interaction Studies Using Gamma Rays” by Gerry Share