cosmic ray acceleration and shocks in heliosphere

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SC4, Lebedev Institute, Moscow, Russia, 2009.05.18

a short discussion on

- cosmic ray acceleration basics
  - propagation
  - acceleration
- observational evidences
  - shocks in heliosphere: termination shock, coronal mass ejection driven shocks, planetary and cometary bow shocks, co-rotating interaction regions, merged interaction regions, …

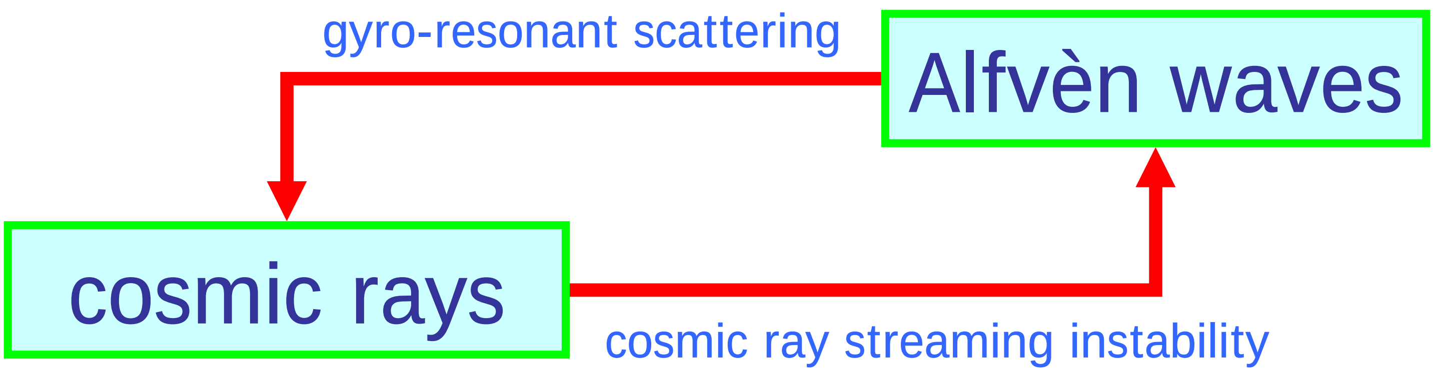
CR acceleration in a nutshell

- cosmic rays are coupled to thermal plasma by magnetic irregularities
  - MHD waves, turbulence
  - gyro-resonant scattering
    (gyro-radius ~ wavelength of waves)
- cosmic ray streaming generates waves
- the magnetic irregularities are pushing and banging the cosmic rays around
  - random pushing or systematic pushing
  - net gain in particle energy in the process

propagation

CR propagation

- assume enough scattering so that the distribution function is more or less isotropic
- self-excited waves, e.g., forward and backward propagating Alfvèn waves



CR propagation

- cosmic rays couple to plasma via hydromagnetic waves
- waves scatter cosmic rays (e.g., gyro-resonant scattering)
- cosmic rays advect (and drift) and diffuse in space and momentum
- waves are excited when cosmic rays stream through the plasma
- equations for CR transport and wave energy exchange (e.g., Alfvèn waves)

$$\frac{\partial f}{\partial t} + \mathbf{W}' \cdot \nabla f - \nabla \cdot (\mathbf{K} \cdot \nabla f) - \frac{p}{3} \nabla \cdot \mathbf{W} \frac{\partial f}{\partial p} - \frac{1}{p^2} \frac{\partial}{\partial p} \left(p^2 D \frac{\partial f}{\partial p} \right) + \frac{\partial b f}{\partial p} = Q$$

adiabatic energy transfer

spatial diffusion

momentum diffusion

other energy loss

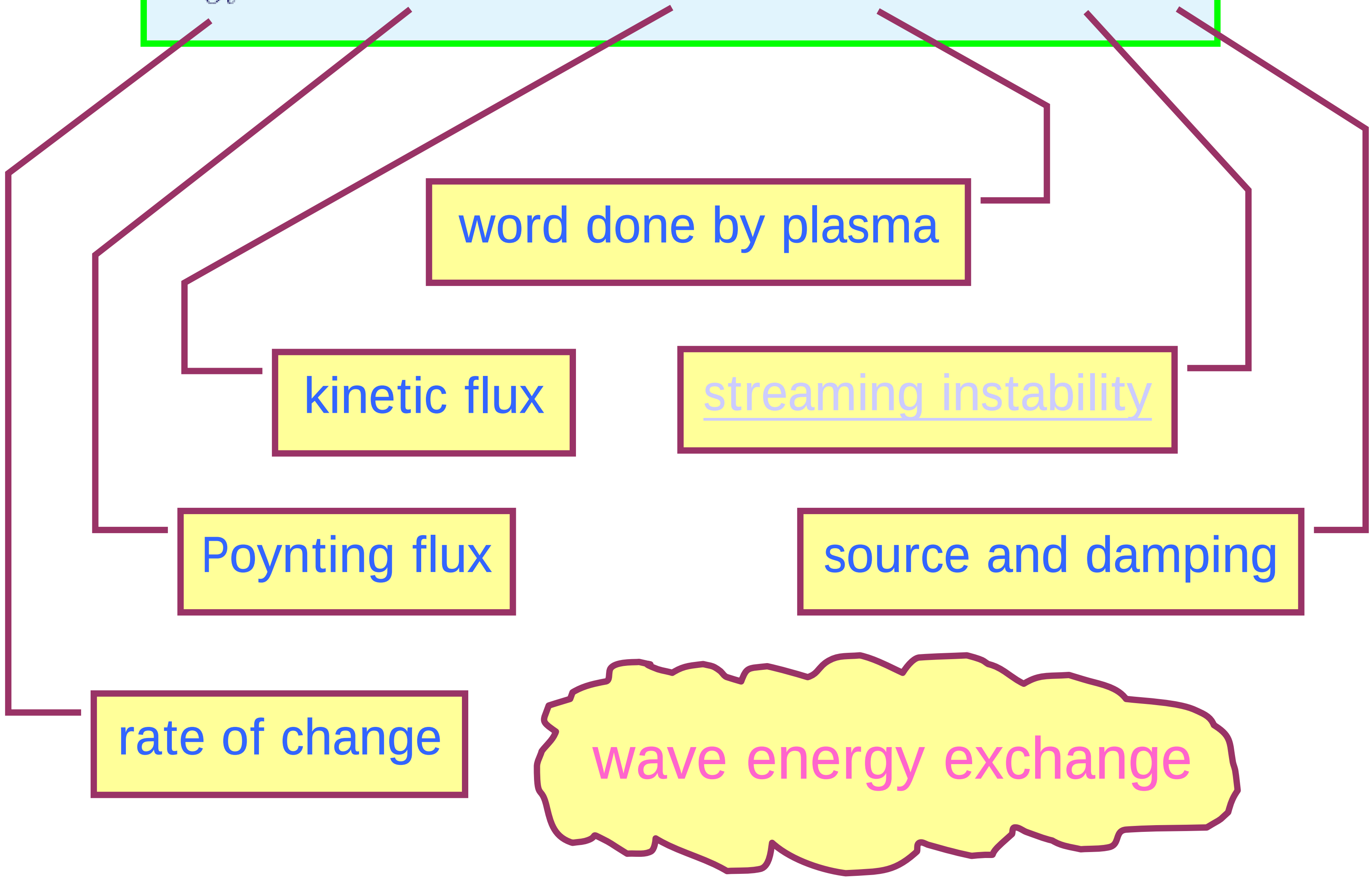
advection

source

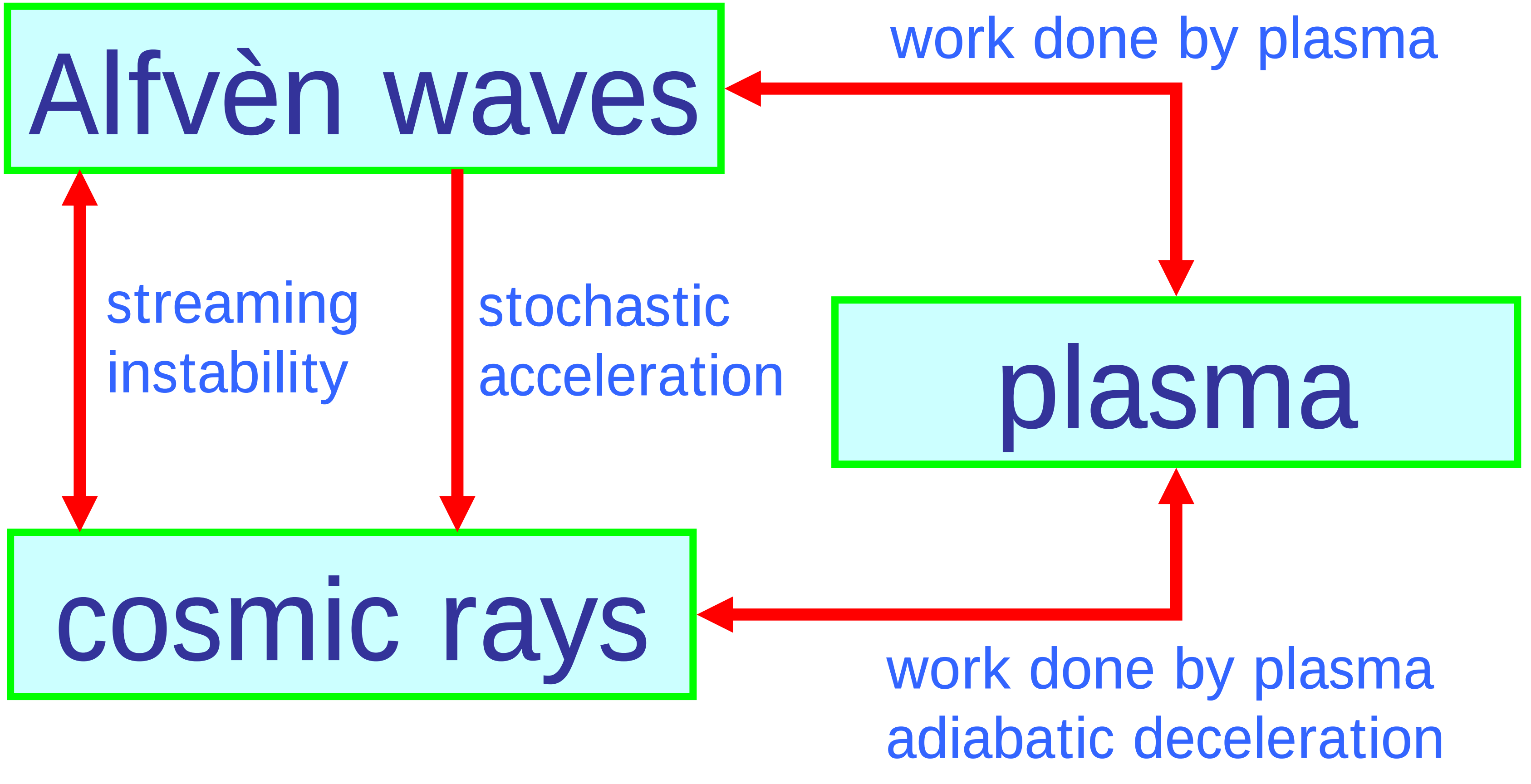
rate of change

cosmic ray propagation

$$\frac{\partial \Sigma_\pm}{\partial t} + \nabla \cdot \left[\left(\mathbf{U} \pm V_\mathrm{A} \mathbf{b} \right) \Sigma_\pm + \tfrac{1}{2} \mathbf{U} \Sigma_\pm \right] - \mathbf{U} \cdot \nabla \left(\tfrac{1}{2} \Sigma_\pm \right) - \sigma_\pm \Sigma_\pm = \mathcal{L}_\pm$$



energy exchange



energy exchange

- cosmic rays
  - gain or loss energy via work done by plasma, adiabatic deceleration, cosmic ray streaming instability
  - gain energy via stochastic acceleration
- Alfvèn waves
  - gain or loss energy via work done by plasma, cosmic streaming instability
  - loss energy via stochastic acceleration

acceleration

Fermi acceleration

- energy gain for each collision ($B = V/c$, $\beta = W/c$):
  - $\Delta\epsilon/\epsilon \approx -2\beta\cos\theta + 2\beta^2$ (for $B \approx 1$, $\beta \ll 1$)
- stochastic acc. or second order Fermi process:
  - taking care of probability of head-on and overtaking collisions
  - the average energy gain: $\langle\Delta\epsilon/\epsilon\rangle \approx 4\beta^2/3$
- shock acc. or first order Fermi process:
  - a round trip across the shock (i.e., two collisions)
  - the average energy gain: $\langle\Delta\epsilon/\epsilon\rangle \approx 4\beta/3$
- both first and second order Fermi processes can produce power law

how to get a power law?

- after each interaction or acceleration
  - the ratio of the new energy to old energy is constant $\epsilon_1/\epsilon_0 = A$
  - particles retain in the acceleration site with a certain probability $n_1/n_0 = E < 1$
- after m interactions there are $n = n_0 E^m$ particles with energies $\epsilon = \epsilon_0 A^m$
- thus a power law:
  - $n(>\epsilon) = n_0(\epsilon/\epsilon_0)^{-\alpha}$, $\alpha = -\log E/\log A$

how to get a power law?

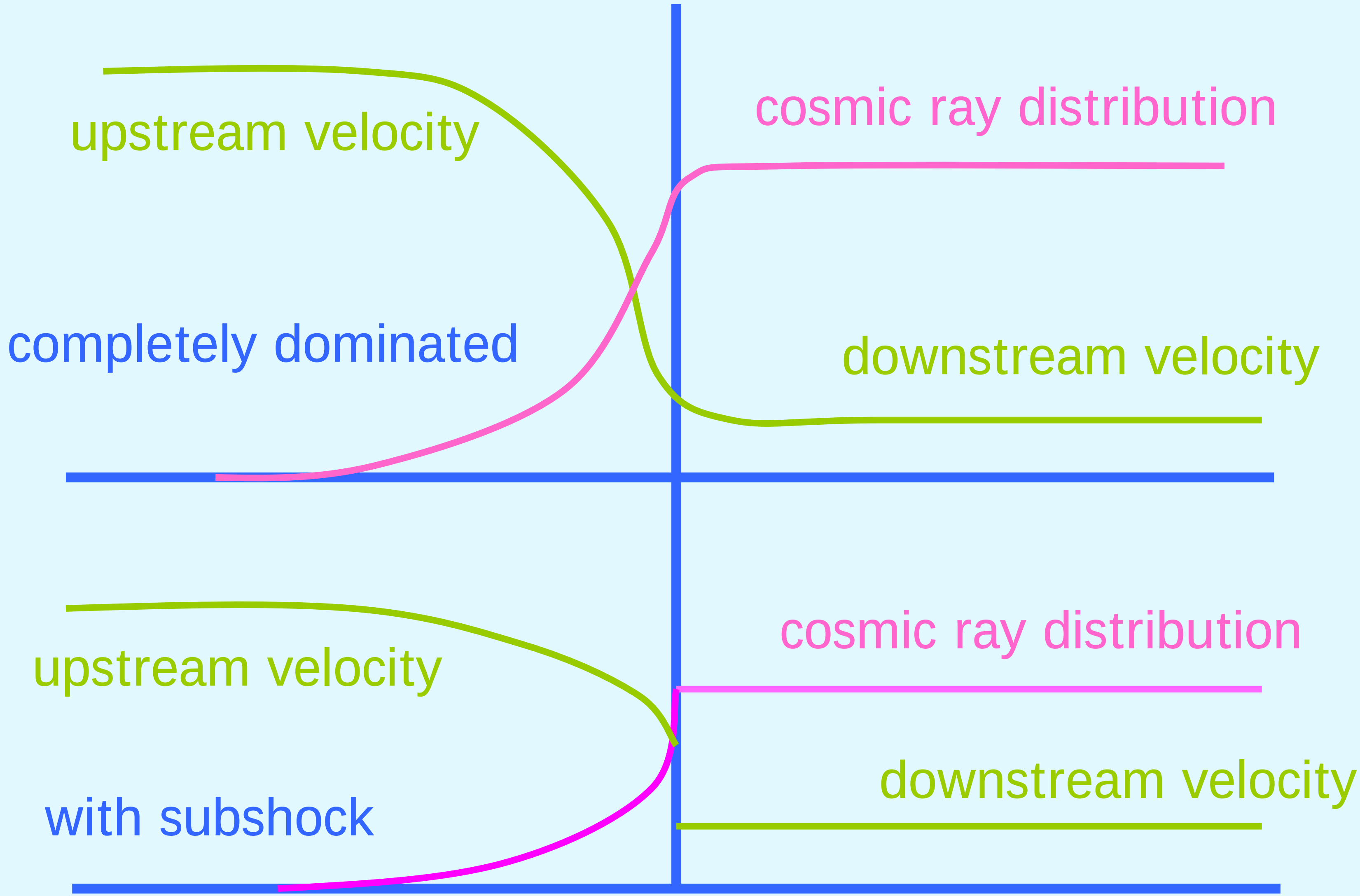
- particle gain energy at time scale τ_a (or all ϵ)
  - $\epsilon = \epsilon_0 \exp(t/\tau_a)$
- particle escape at time scale τ_e (or all ϵ)
  - $n(>\epsilon) = n_0 \exp(-t/\tau_e)$
- thus a power law:
  - $n(>\epsilon) = n_0(\epsilon/\epsilon_0)^{-\alpha}$, $\alpha = \tau_a / \tau_e$
  - smaller τ_a gives harder spectrum

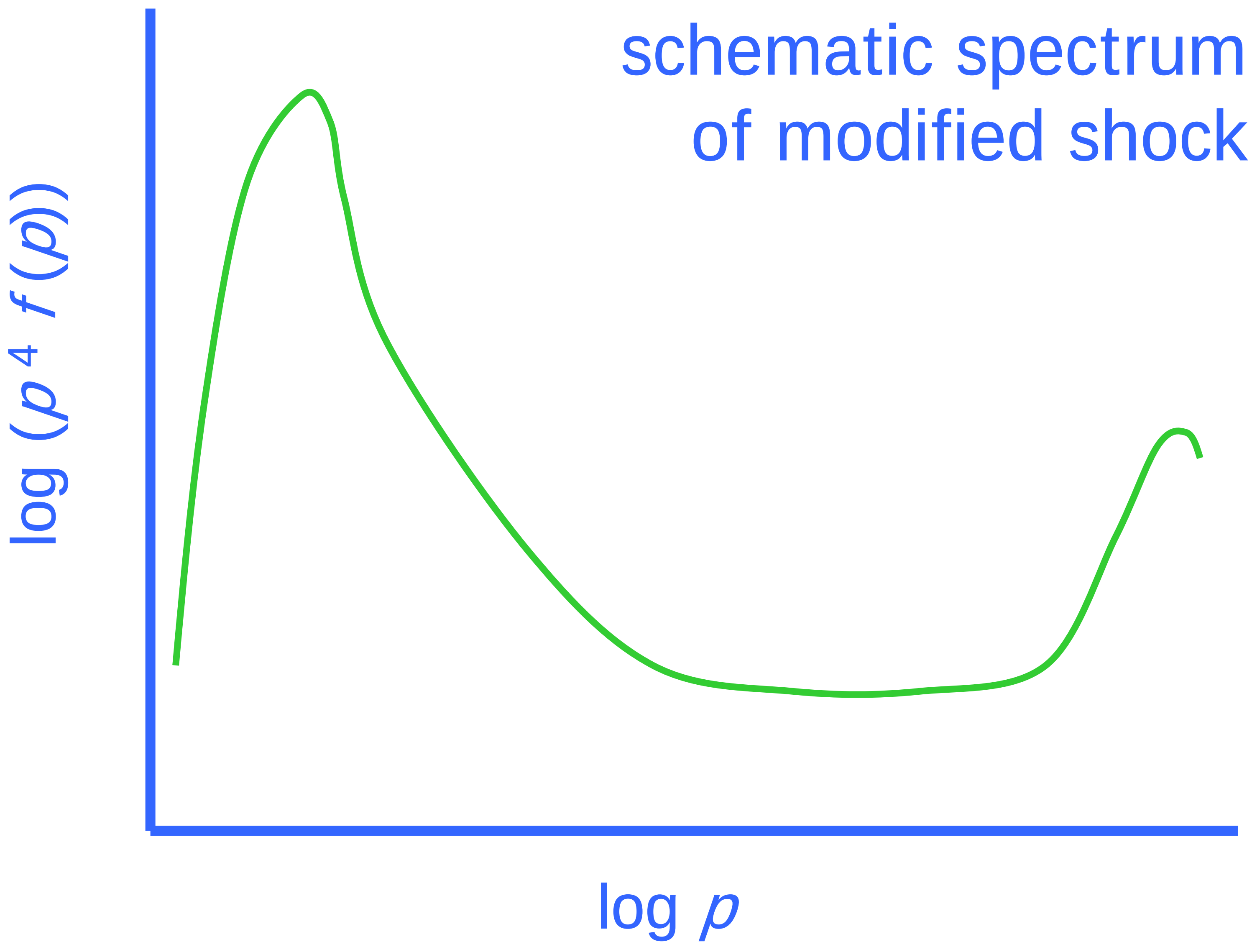
diffusive shock acceleration

- plane shock with upstream velocity U and compression ratio R
- $A \approx 1 + 4(R\text{-}1)U/3Rc$
- $E \approx 1 - 4U/Rc$
- power law index: $\alpha = 3/(R\text{-}1)$
- differential spectral index: $\alpha+1 = (R+2)/(R\text{-}1)$
  - for strong shock and $\gamma = 5/3$, $\alpha+1 = 2$
  - for strong shock and $\gamma = 4/3$, $\alpha+1 = 3/2$

modified shock

- plane shock acc. is very efficient
- backreaction on the flow
- cosmic ray dominated shock
  - may has a precursor and a subshock
  - or may become a smooth transition altogether
  - overall compression ratio may increase quite a lot
- high energy particles have larger diffusion coefficient and feel a larger compression ratio
  - harder spectrum at high energy
  - concave spectrum for strong shocks


upstream velocity
cosmic ray distribution
completely dominated
downstream velocity
upstream velocity
cosmic ray distribution
downstream velocity
with subshock



schematic spectrum
of modified shock
log (p^4 f(p))
log p

observational evidences

shocks, shocks everywhere

from interplanetary shocks to
stellar wind termination shocks to
supernova remnant shocks to
merger shocks to ...

heliospheric or interplanetary shocks (collisionless)

- termination shock
- CME driven shocks
- planetary and cometary bow shocks
- CIRs and MIRs
- ...

- *in situ* measurements
- energy spectrum
- composition
- temporal variation
- magnetic field
- waves
- plasma properties
- seed
- ...

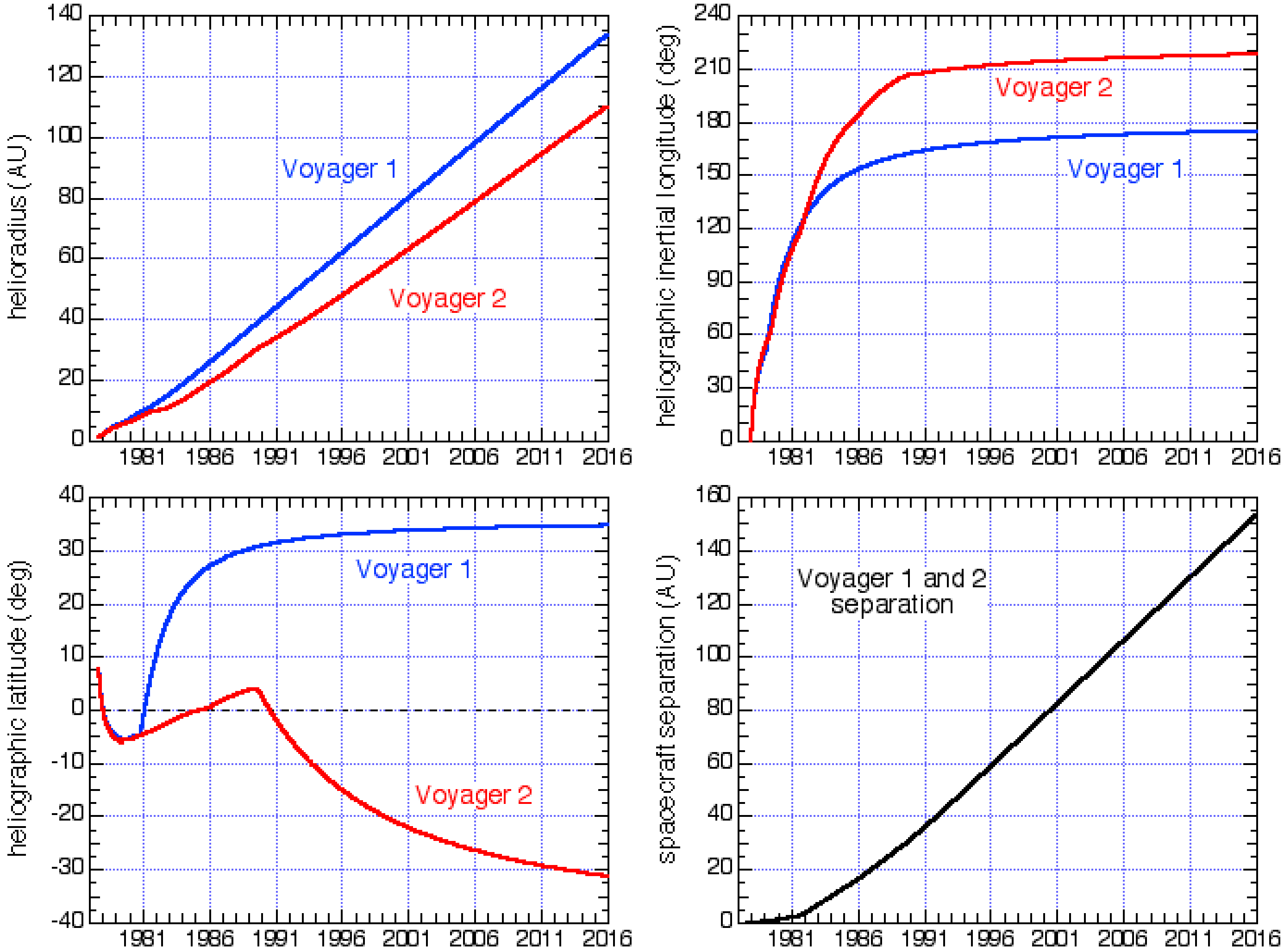
termination shock

voyager 1 and 2
have crossed
the heliospheric
termination shock

Voyager 1 & 2
(Voyager Interstellar Mission,VIM)

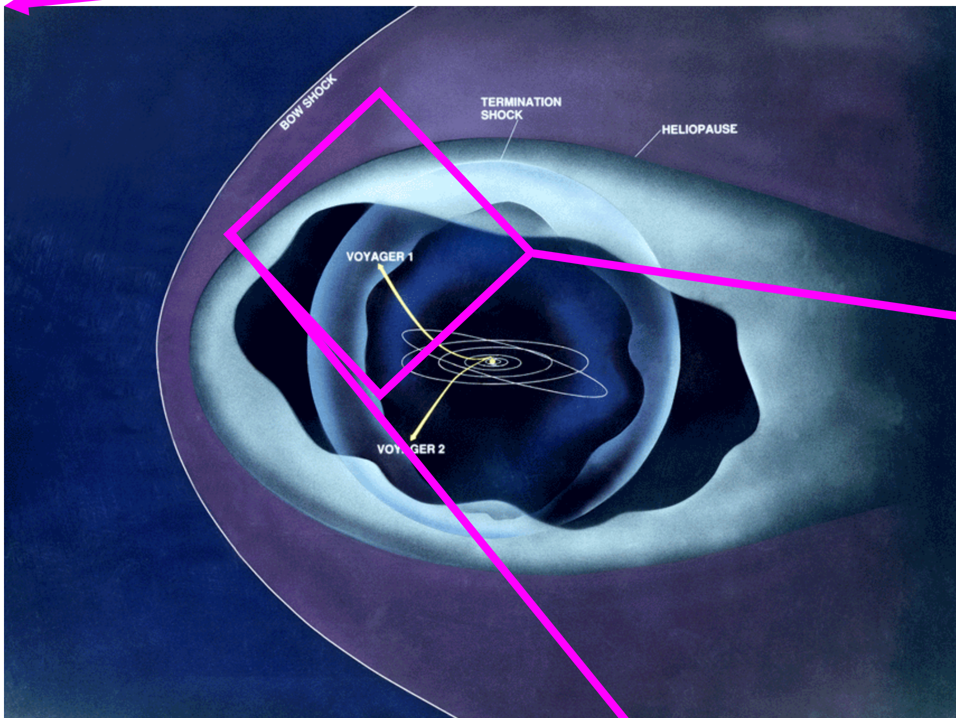
	launch	position at 2009.05 (heliospheric inertial)	termination Shock	heliopause
Voyager 1	1997.09.05	34.3º latitude 173.4º longitude 110 AU at 3.6 AU/year	crossed TS on 2004.12.16 at 94 AU	130-150 AU? in 2014-2017?
Voyager 2	1997.08.20	-28.5º latitude, 216.7º longitude 89 AU at 3.3 AU/year	crossed TS on 2007.08.30 at 84 AU	130-150 AU? in 2014-2017?

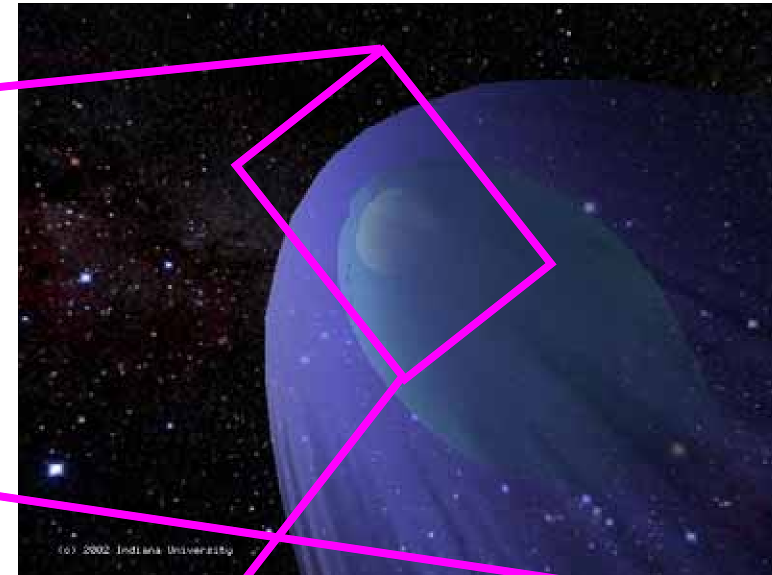
trajectory of Voyager 1 & 2

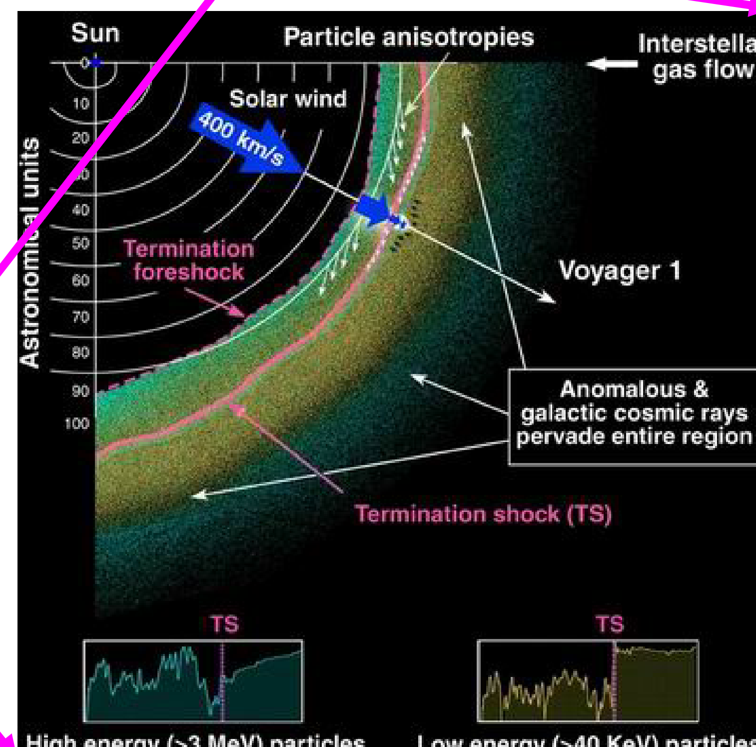


http://sd-www.jhuapl.edu/VOYAGER/iptraj.html

voyage to the edge of heliosphere

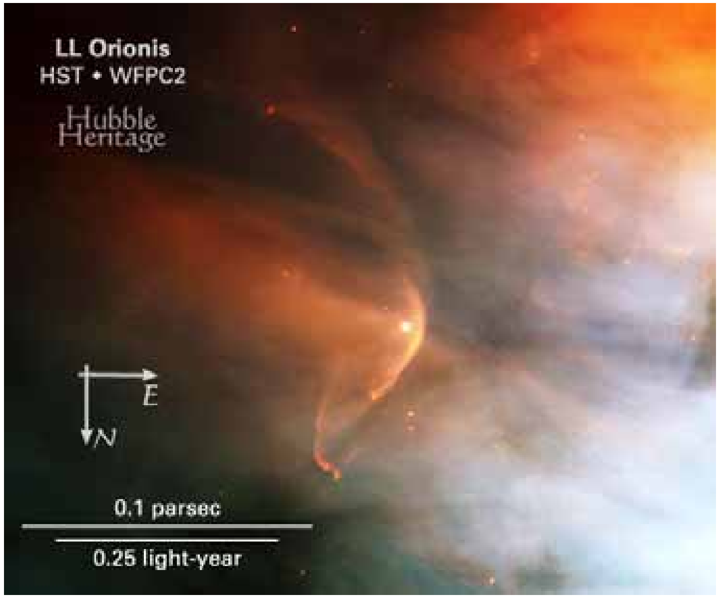




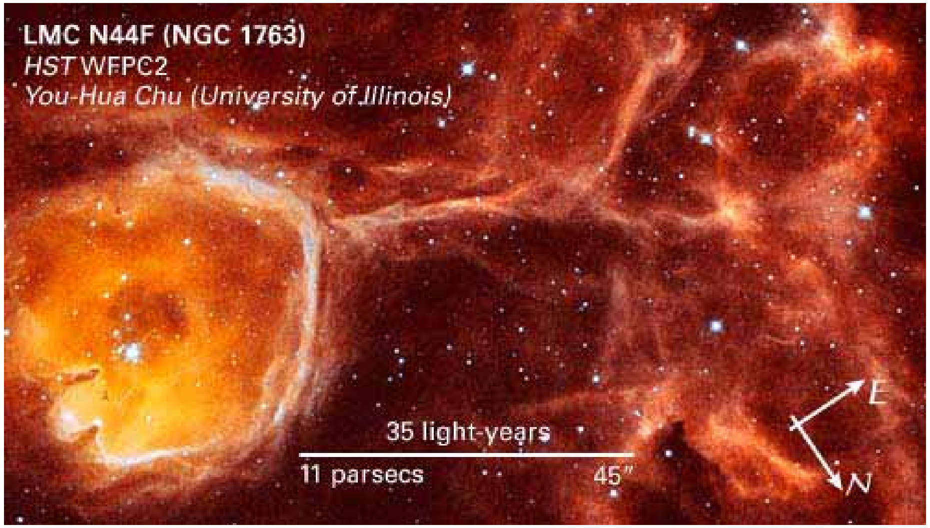


counterclockwise from top right
Frisch et al. APOD20020624
voyager.jpl.nasa.gov/mission.html
Decker et al. (2005)

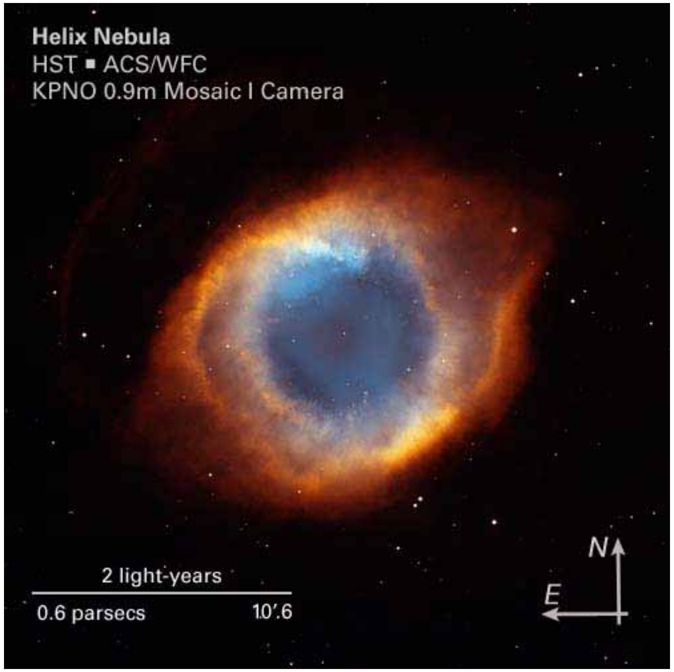
heliosphere is just one more bubble in the sky but smaller



bow shock near young star



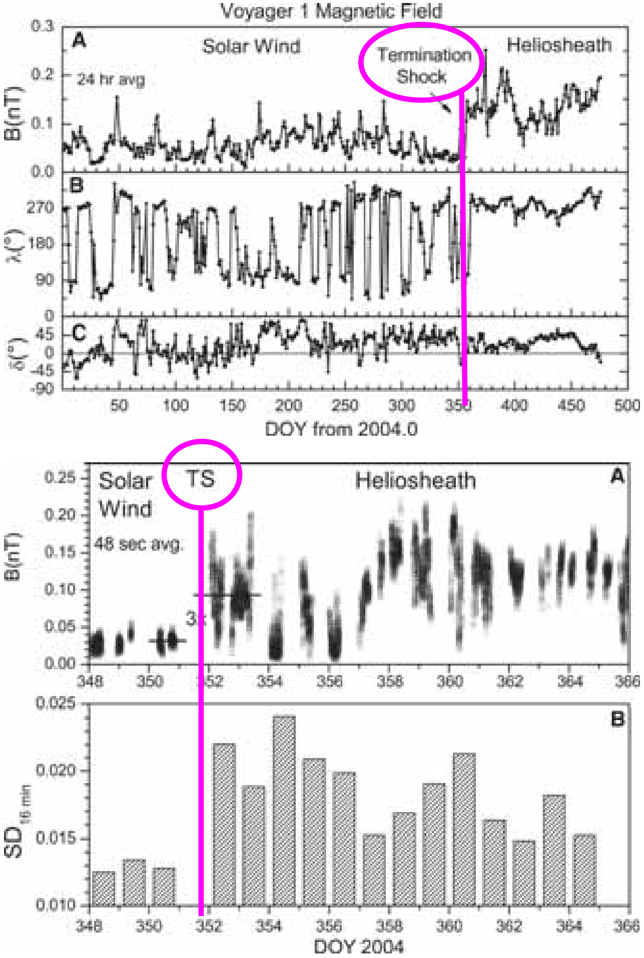
wind bubble from hot star



planetary nebula

how do we know Voyager 1 & 2 crossed the termination shock?

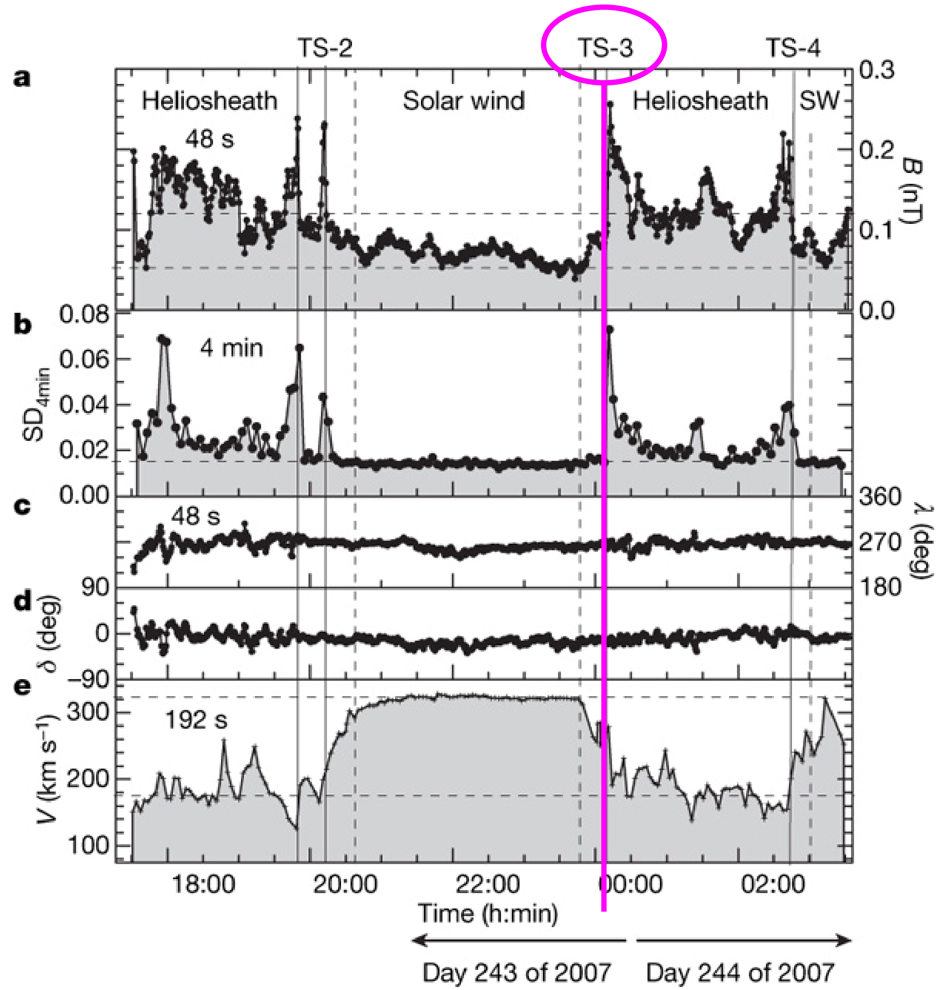
- Voyager 1 crossed the shock at 94 AU
- magnetic field strength and its fluctuations
  - 3 times increase in magnitude right across the shock
  - field in heliosheath is 2.4 times the average upstream field
  - larger fluctuations after shock crossing



Burlaga et al. 2005

supercritical quasi-perpendicular

- Voyager 2 crossed the shock at 84 AU
- velocity jumps
- 5 shock crossings
  - probably temporal
- TS-3 is a typical supercritical quasi-perpendicular shock

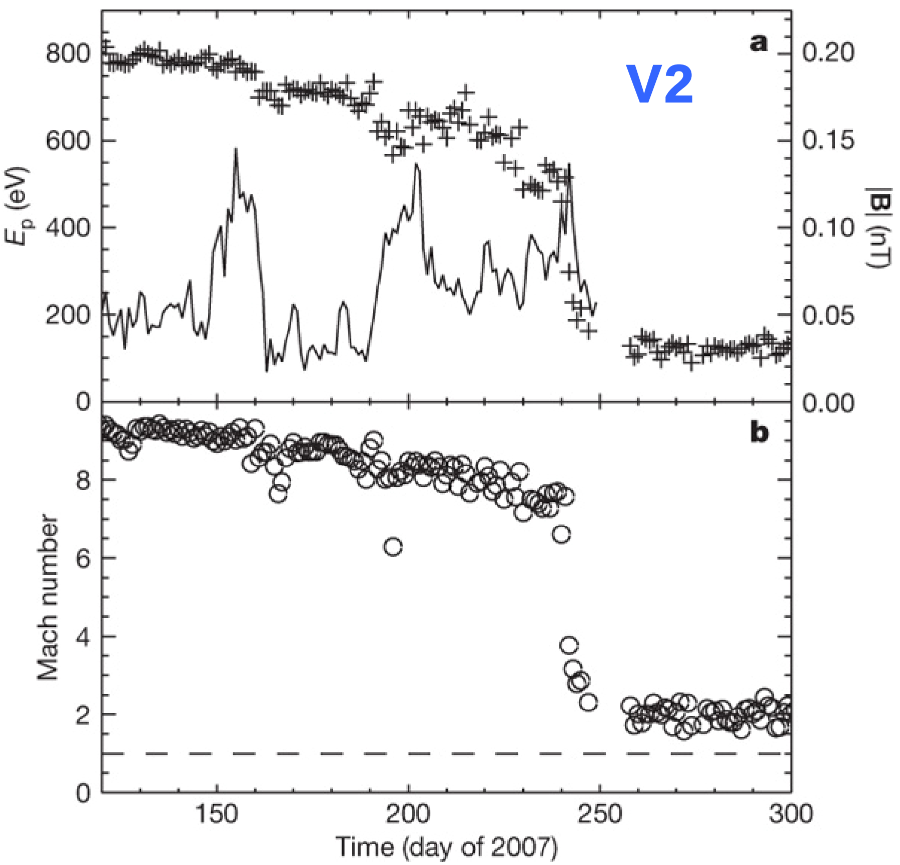


Burlaga et al. 2008

pickup ions dominated

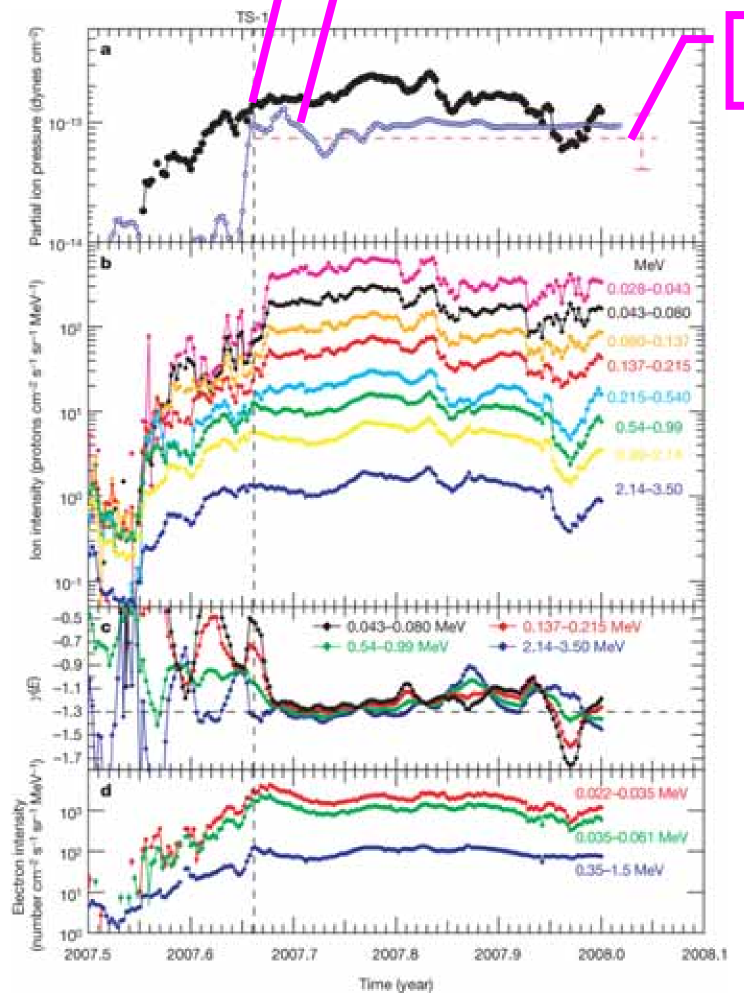
- energy (flow plus thermal) of solar wind measured by Voyager 2 drops ~ 80% across the shock
- supersonic downstream
- large portion of energy goes to pickup ions

Richardson et al. 2008



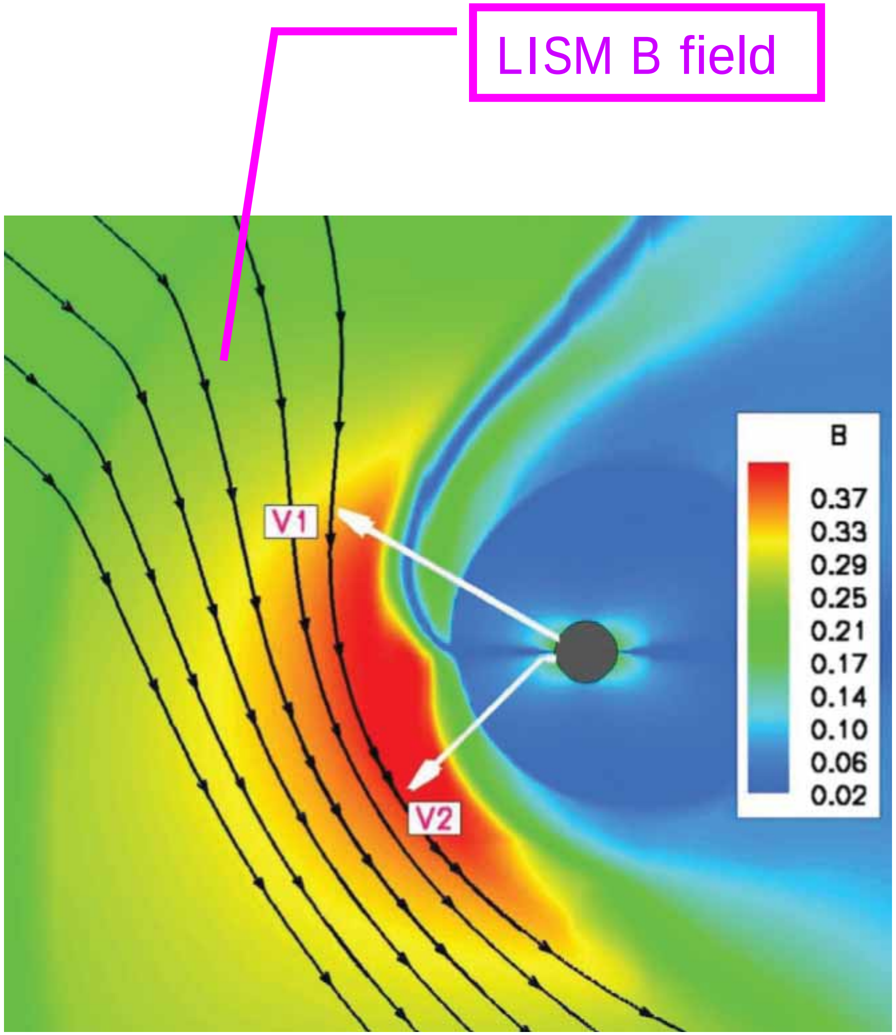
pickup ions dominated

- pressure of energetic ions (several hundreds keV to several MeV) is comparable (or exceeds) both thermal and magnetic pressures
- detected energetic neutral atoms (~ 4-20 keV) is similar to SW pickup ions in spectra
  - pickup ions acclerated by TS and then charge exchange again



Decker et al. 2008

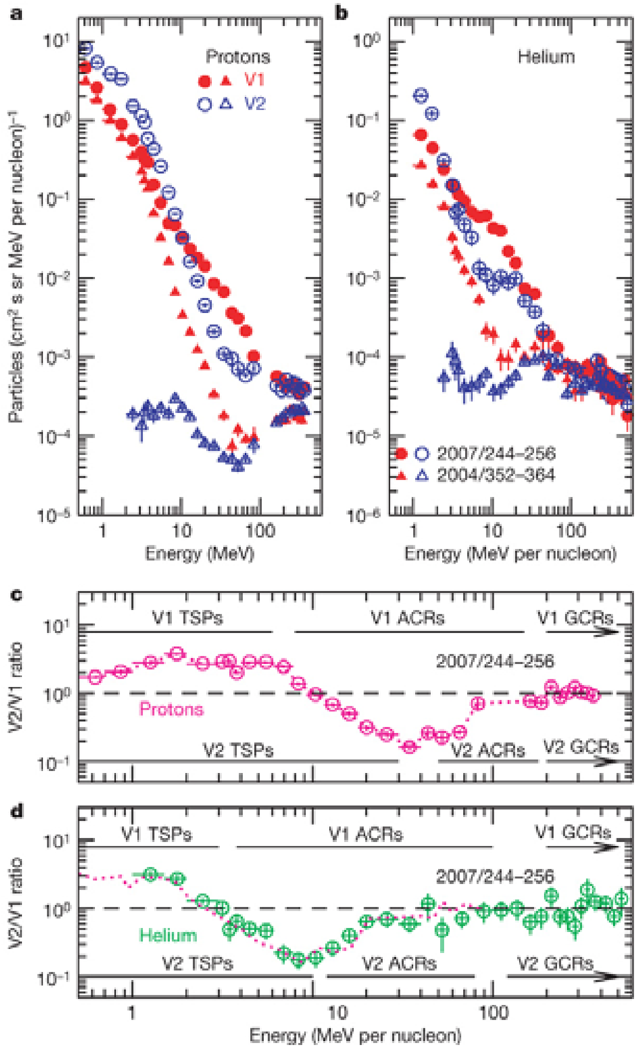
the solar wind
termination shock is a
pick-up ions modified
supercritical
quasi-perpendicular
asymmetric shock



Opher et al. 2008

how about energetic particles?

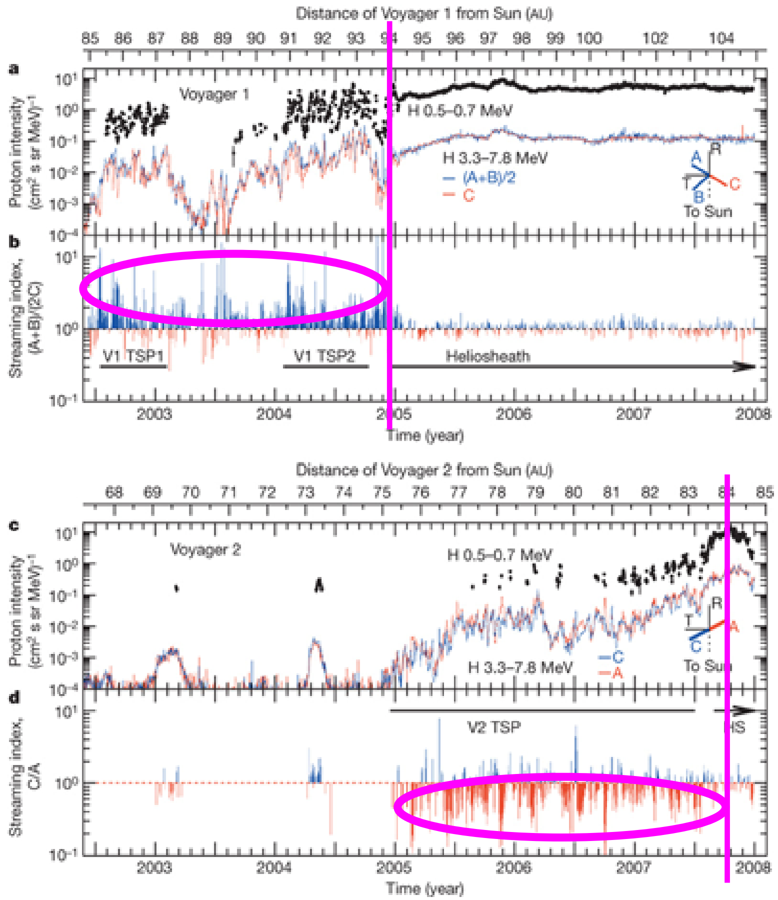
- termination shock particles (TSPs)
  - e.g., protons at several MeV
- anomalous cosmic rays (ACRs)
  - roughly 10-100 MeV/nucleon
  - He, N, O, Ne, etc.
- galactic cosmic rays (GCRs)
  - >100 MeV
  - mostly proton



Stone et al. 2008

termination shock particles (TSPs)

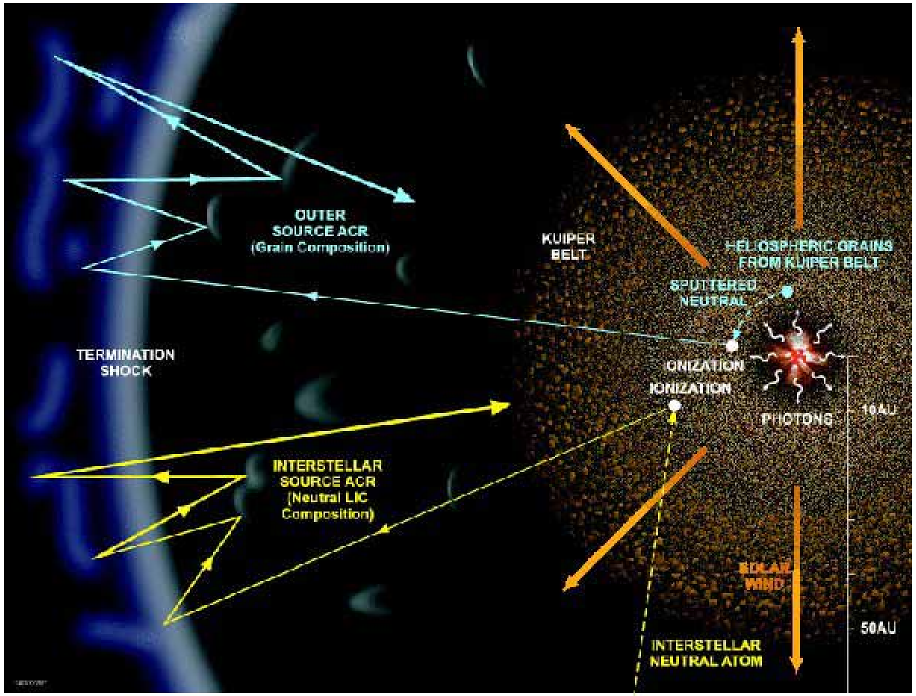
- TSPs upstream of the shock at V1 is anti-sunward, while at V2 is sunward (connection to the source?)
- roughly isotropic in the heliosheath
- strongly affected by heliospheric disturbances such as MIRs



Stone et al. 2008

anomalous cosmic rays (ACRs)

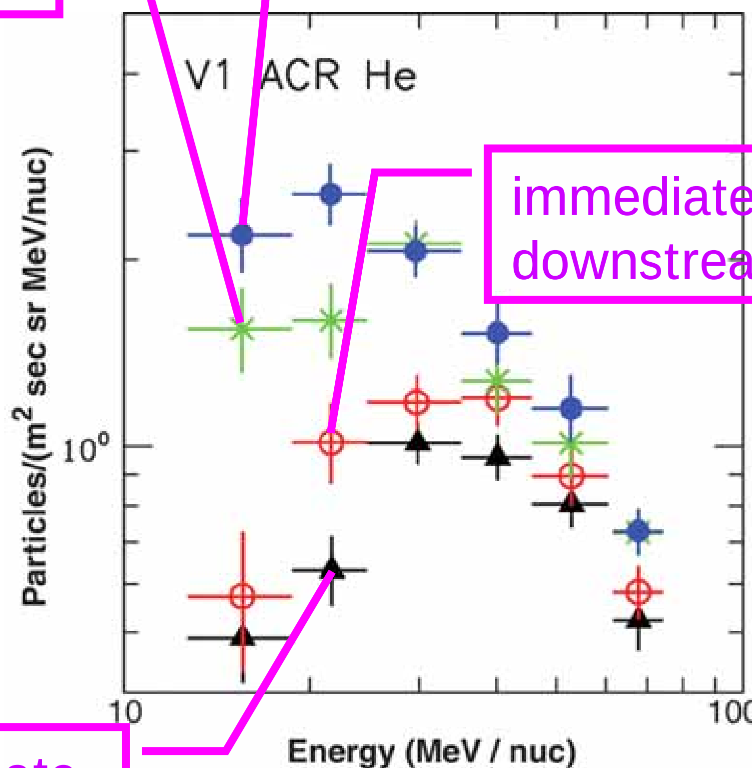
- interstellar neutrals ionized by solar UV
- pickup by solar wind at ~ 1 keV/nucleon
- then accelerated by TS (and beyond?) to > 10 MeV/nucleon



www.swri.org/3pubs/ird2004/Synopses/159352.htm

ACRs

- for both shock crossings ACR intensity does not peak at the shock as expected
  - still substantially modulated in the heliosheath
- the spectrum does not change and the intensity does not increase cross the shock

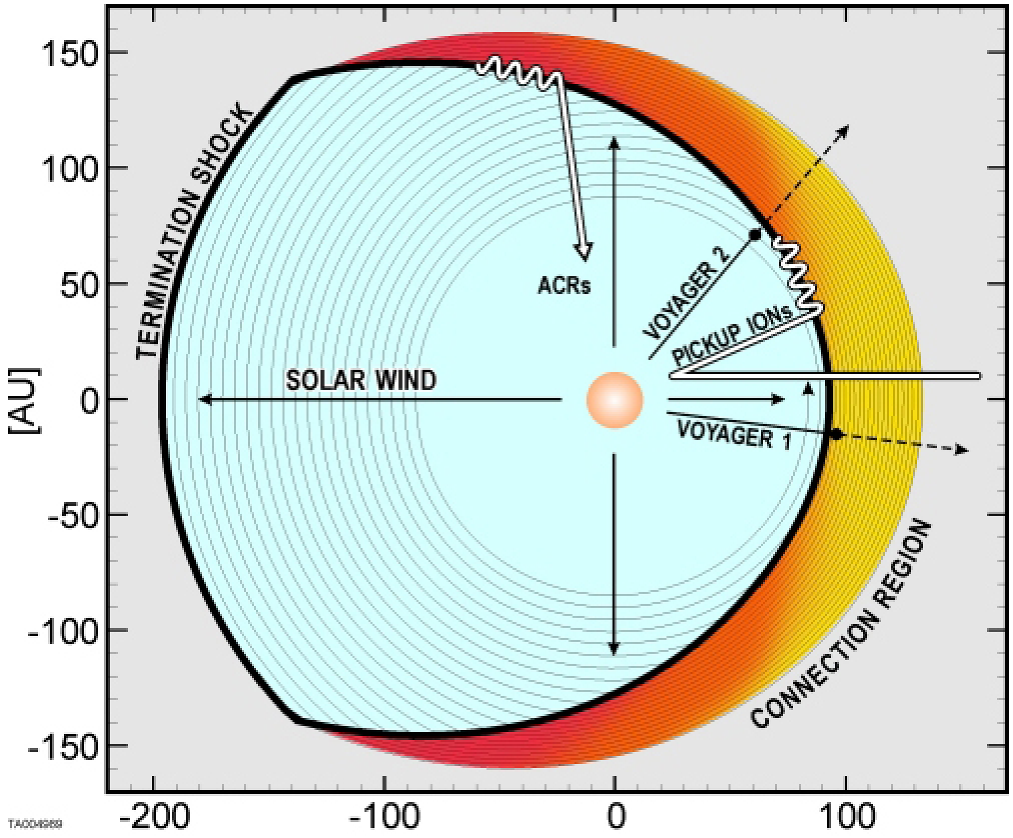


Stone et al. 2005

ACRs

- low energy ions (< 3 MeV per nucleon) are accelerated rapidly in nearby TS, while ACRs are accelerated further away
- continue modulation in heliosheath is due to temporal variation (?) or magnetic topology (?)
- source of ACRs may be at the flank or tail of the shock (a blunt TS) or in the heliosheath
  - diffusive shock acceleration may still be alright
- both ACRs and TSPs are accelerated pickup ions
  - two stages acceleration(?): first accelerate TSPs, then accelerate ACRs later

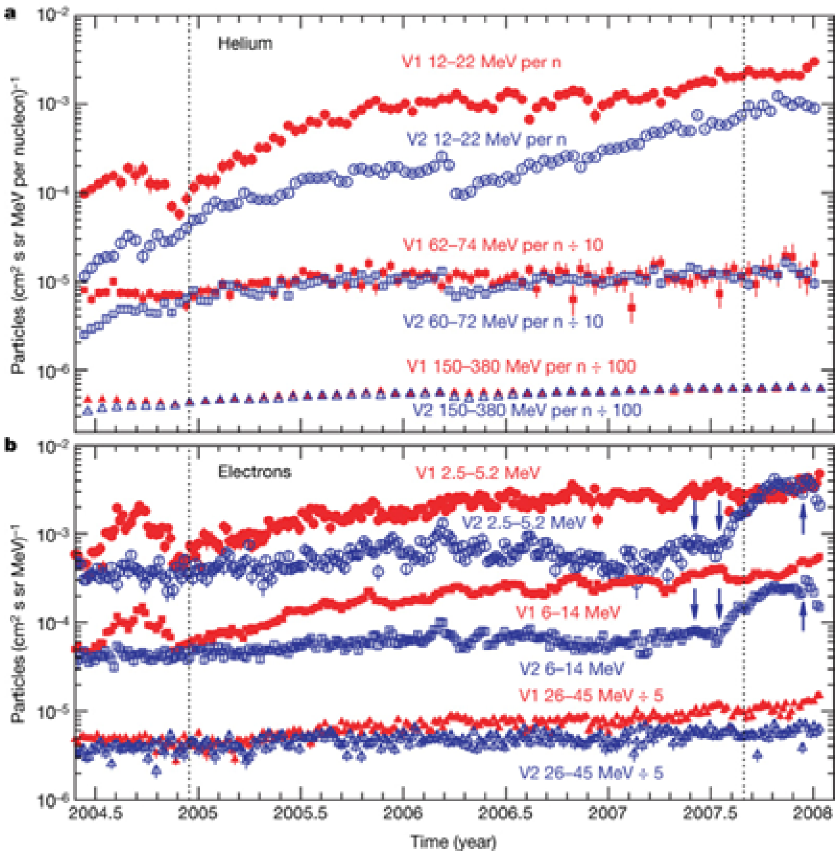
blunt termination shock



McComas and Schwadron 2006

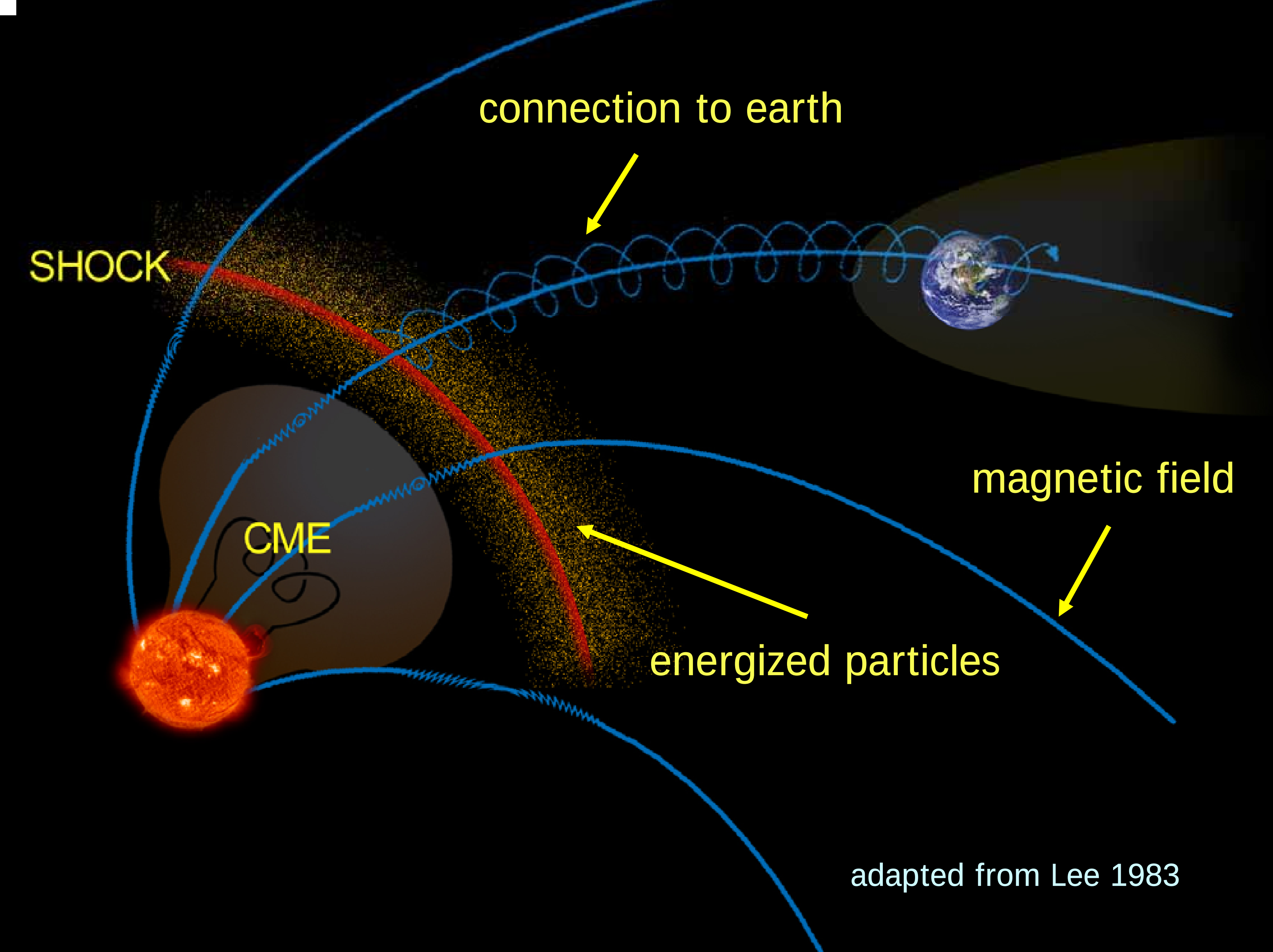
galactic cosmic rays

- solar modulation
- V1 & V2 measure a small intensity gradient of GCR helium
- either the gradient or modulation is further out in the heliosheath
- or the interstellar GCR flux is lower than expected



Stone et al. 2008

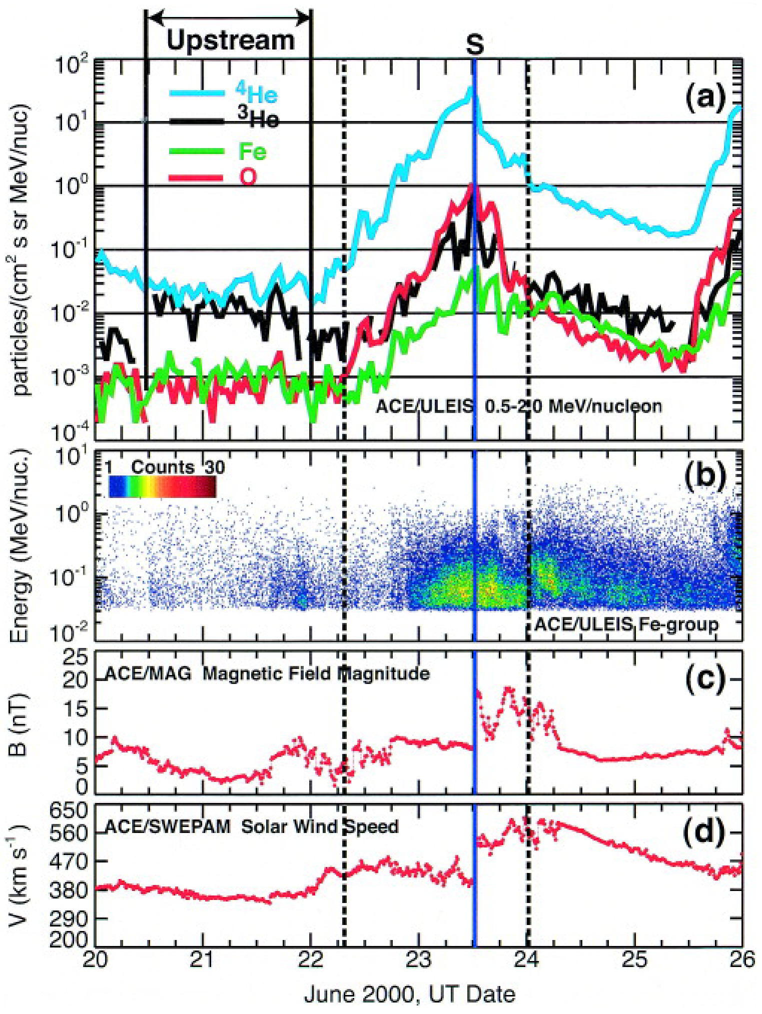
interplanetary shocks


connection to earth
SHOCK
magnetic field
CME
energized particles
adapted from Lee 1983

typical IP shock

- most interplanetary shocks are CME driven shocks
- *in situ* measurements by ACE, SOHO, WIND, Ulysess, Voyagers, IMP8, ISEE3, Goes, etc.
- particles are energized
  - seed population?
  - location?
  - self-excited waves?
  - modified-shock?
  - ...

ACE measurements
2000.06.20~2000.06.26

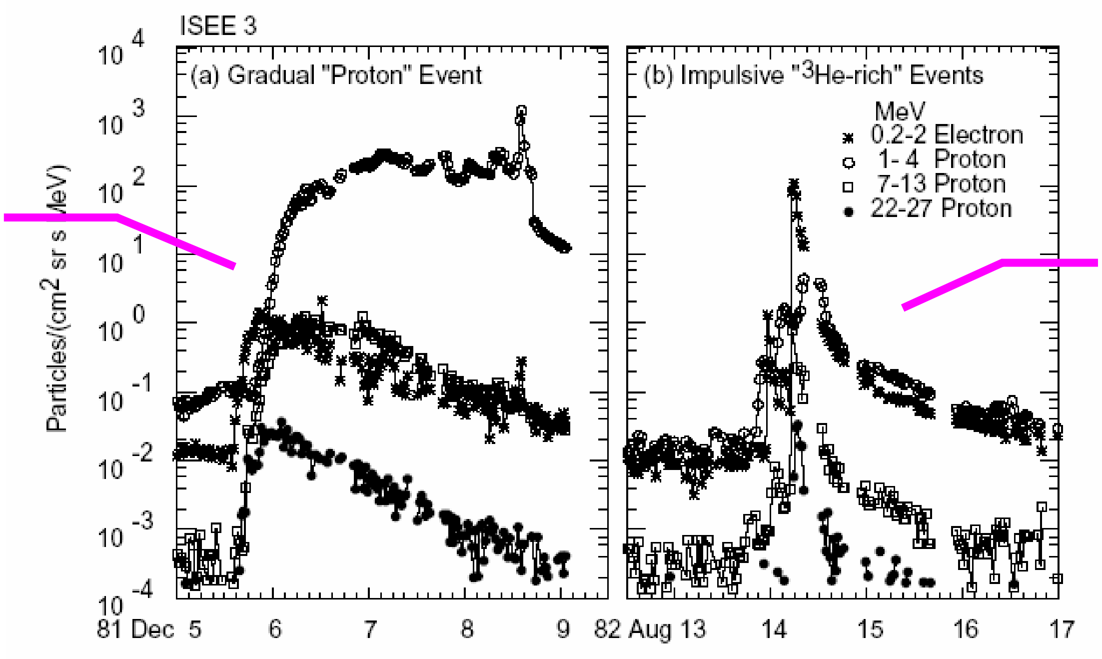


Desai et al. 2003

solar energetic particles (SEPs)

two types: gradual and impulsive
different isotopic compositions

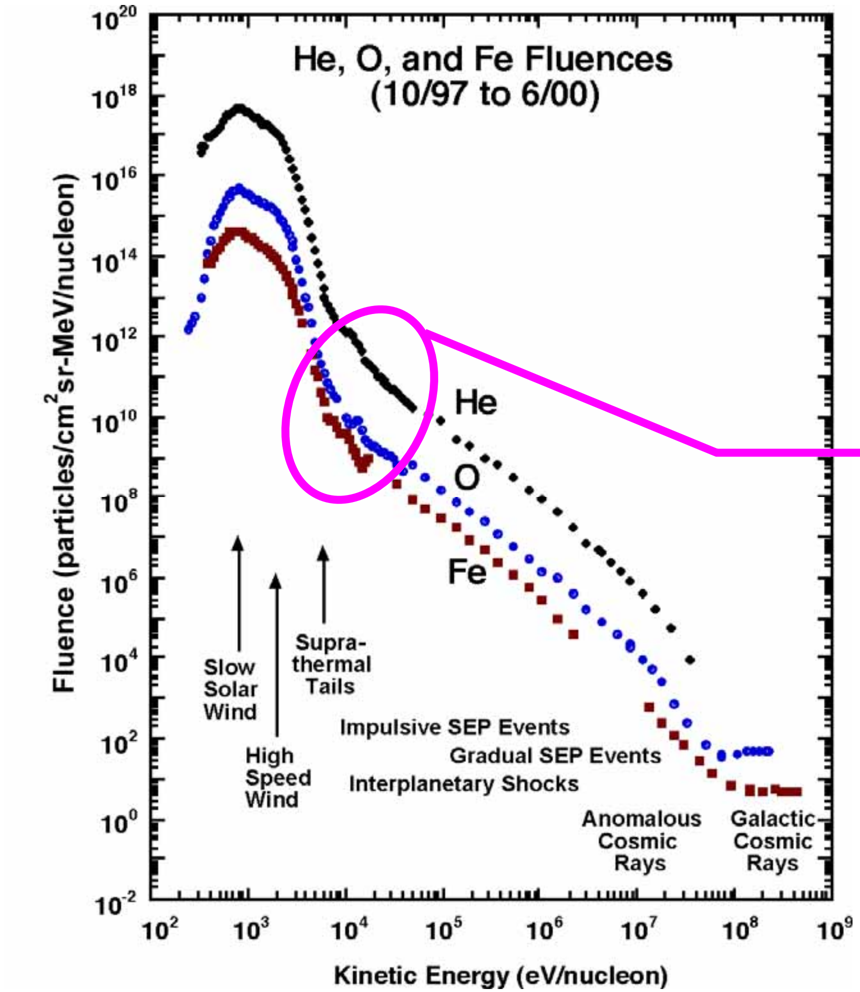
associated with CMEs?



associated with flares?

Reames 1999

spectrum from solar wind to CR energies



Mewaldt et al. 2001

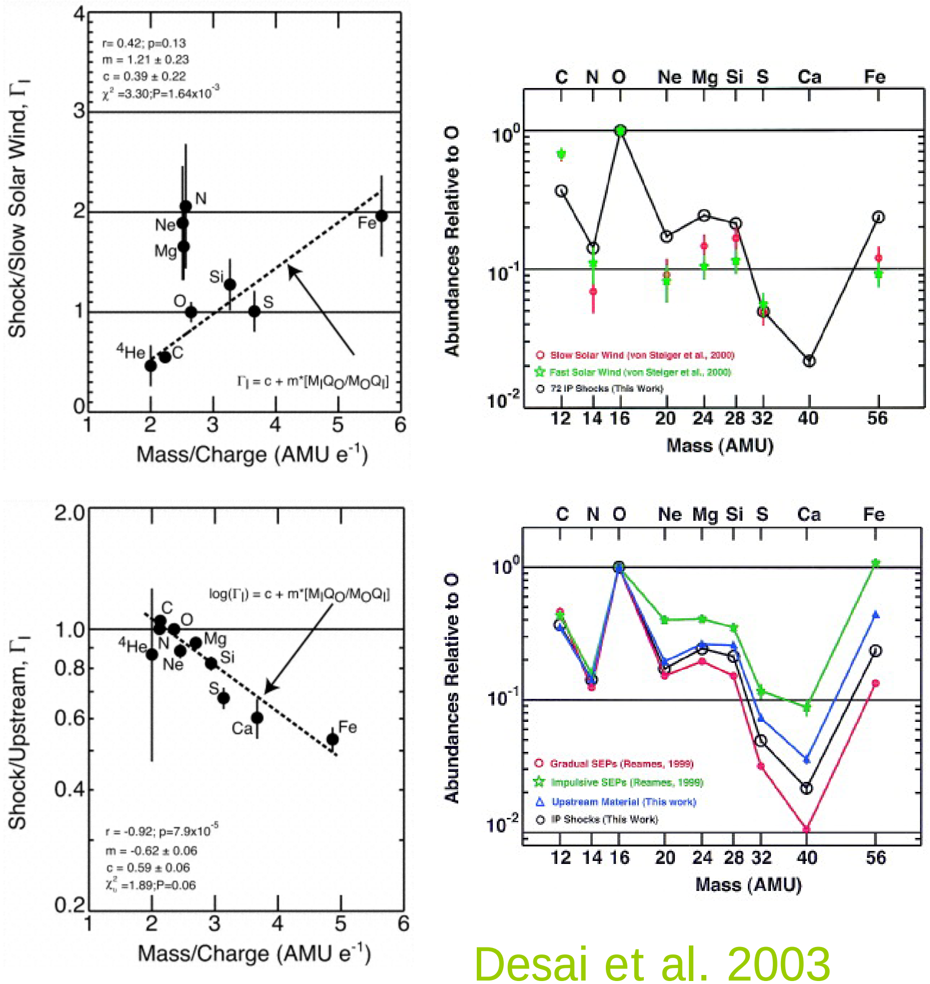
seed?
high energy tail of solar wind?
or pre-accelerated suprathermal ions?

acceleration sites for SEPs

- solar flares or CME driven shocks
  - common view (but not all) is CME driven shocks
- how do we know
  - timing
  - spectrum and intensity of anisotropic ground-level events (GLEs)
  - GLE-associated with CMEs
  - solar gamma ray line flares has little correlation with SEPs
  - ...

seed population

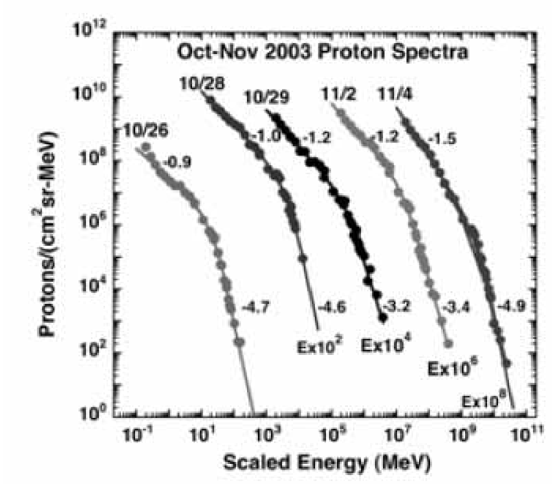
- solar wind ions or suprathermal ions?
- abundance observation of IP shocks at 1 AU indicates seeds come from suprathermal ions pre-accelerated by solar flares or other IP shocks
  - two-stage acceleration
- ^{3}He rich events associated with solar flares

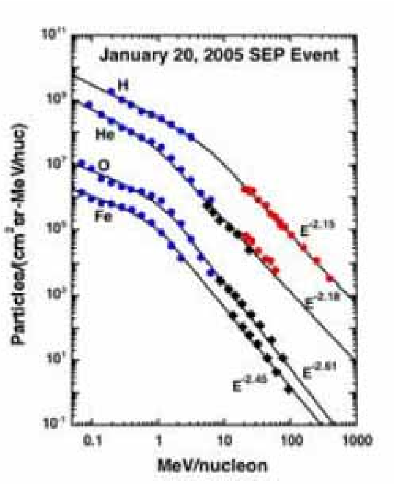


Desai et al. 2003

self-excited waves

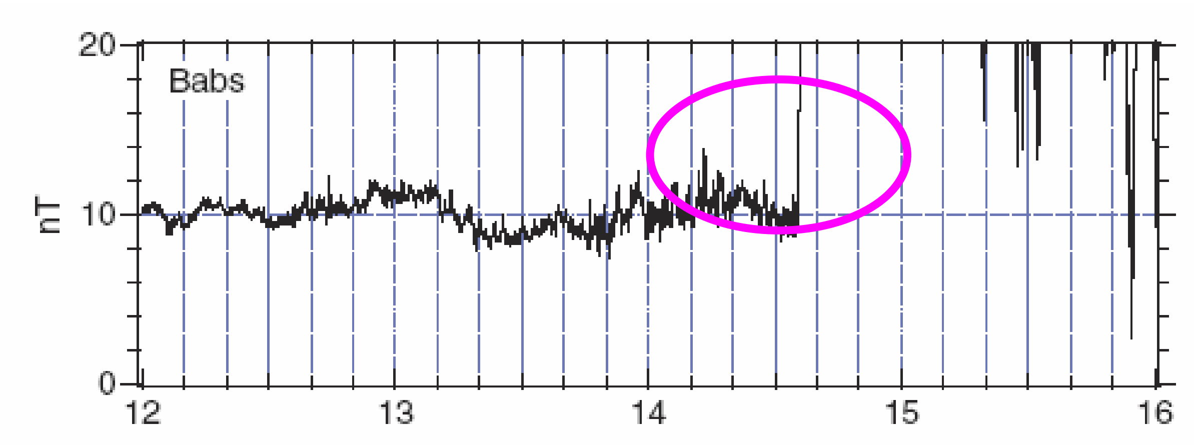
- the idea is waves excited upstream of the shock by energetic particles trap the particles for further acceleration
- the breaks in these spectra may be an indication of proton-excited Alfven waves (e.g., due to saturation)





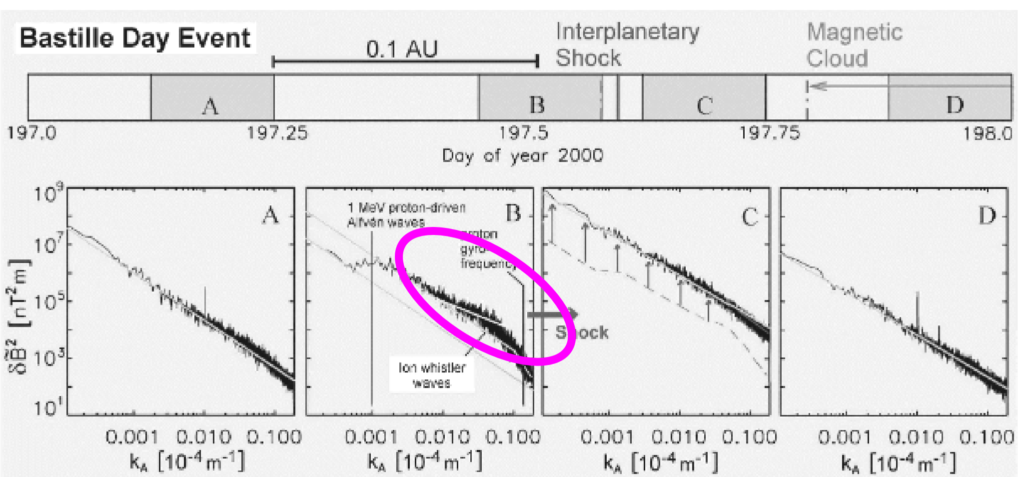
Mewaldt et al. 2005

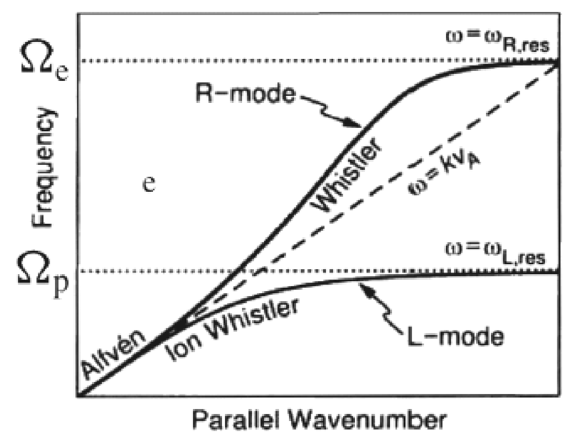
in situ measurement



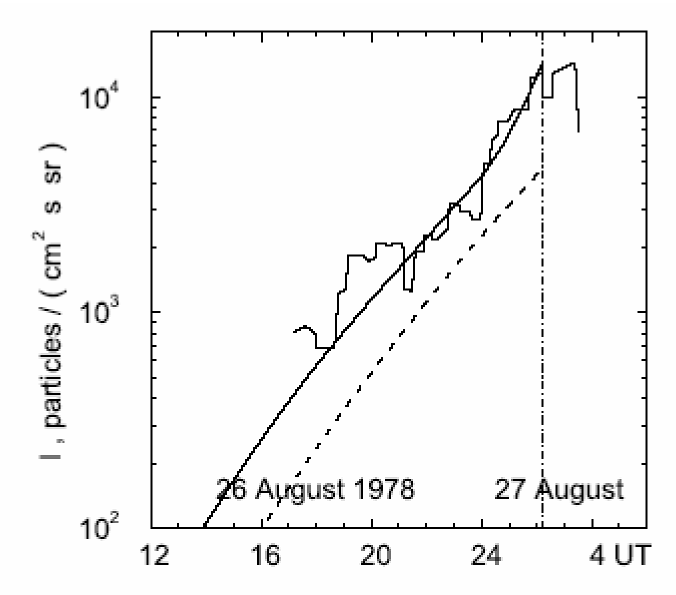
2000.07.15 event
(Bastile day event)

Terasawa et al. 2006

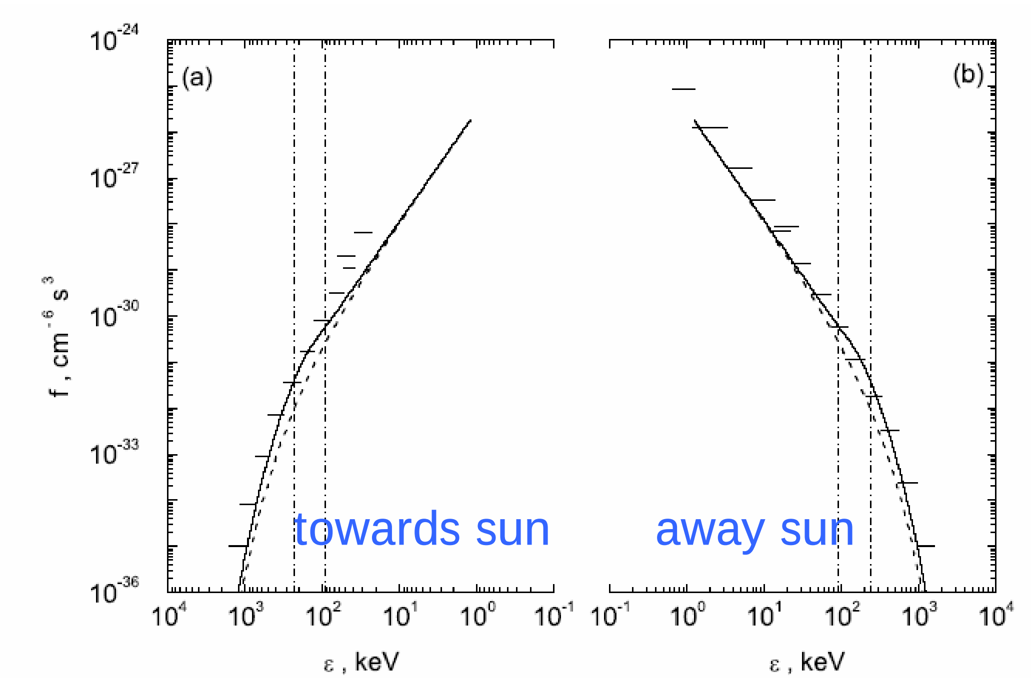




ACE news #91, 2005.08.30 (Kallenbach & Bamert)



quantitative fitting of an energetic storm particle (ESP) event on 1978.08.27

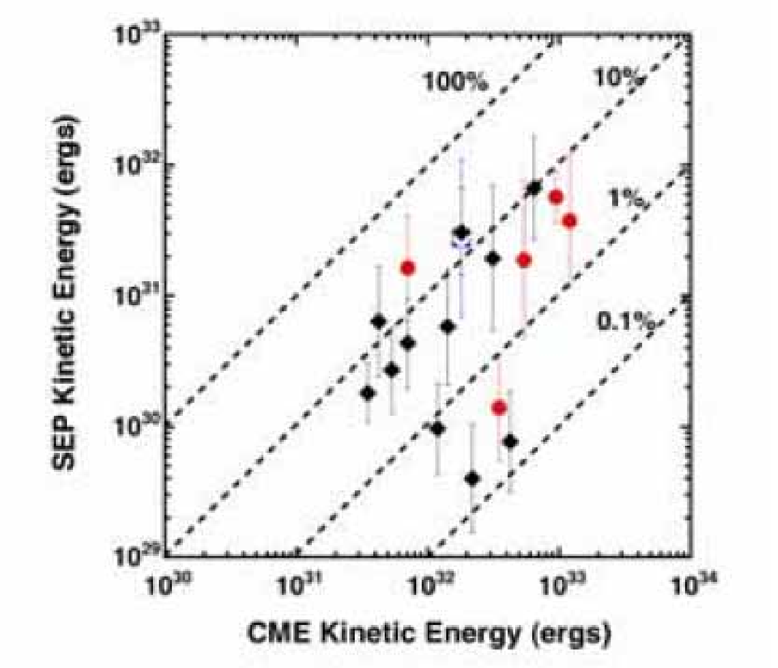


solid line (dotted line):
with (without)
self-excited Alfven waves

Berezhko and Taneev 2007

modified shock?

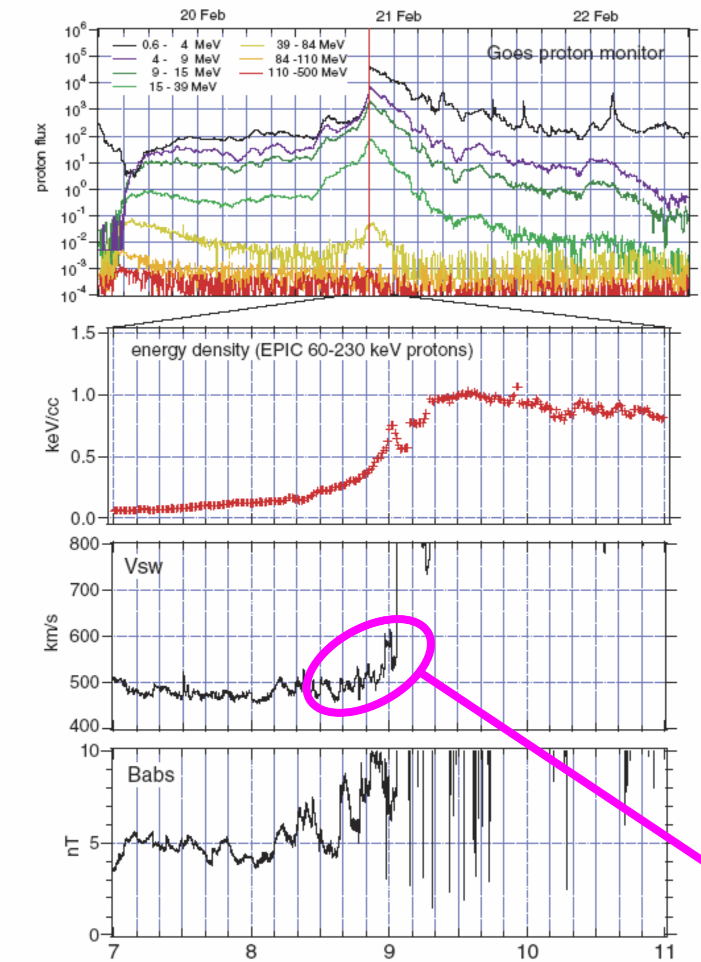
- at strong shock, when accelerated particles gain enough energy, backreaction will take place
- SEPs suck up ~10% of CME's energy (dissipation of CME, modified shock?)

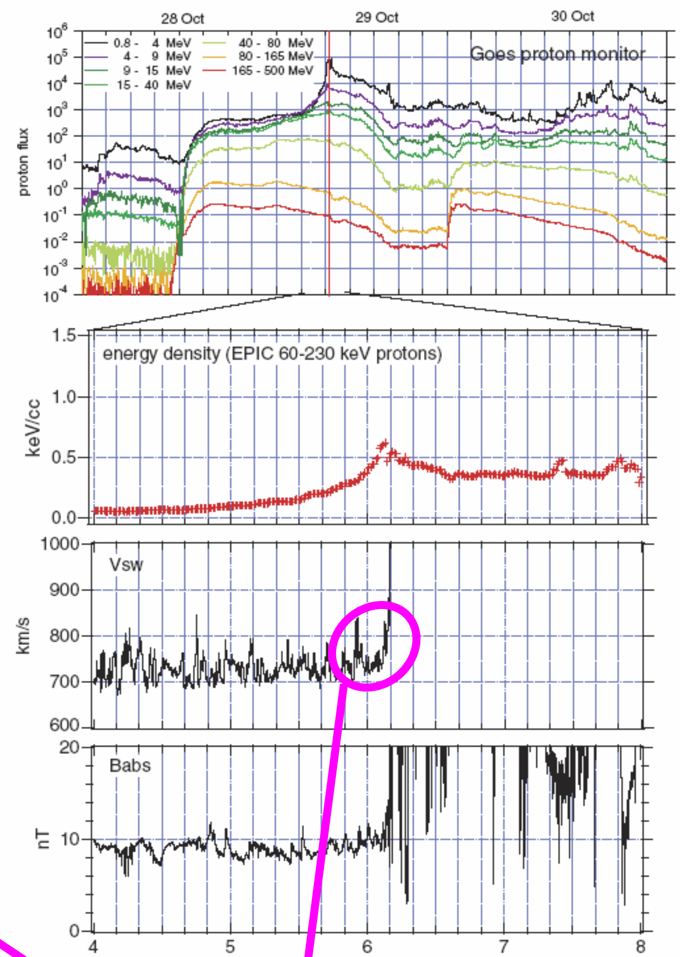


Mewaldt et al. 2005

1994.02.21 event

2003.10.29 event (Halloween event)



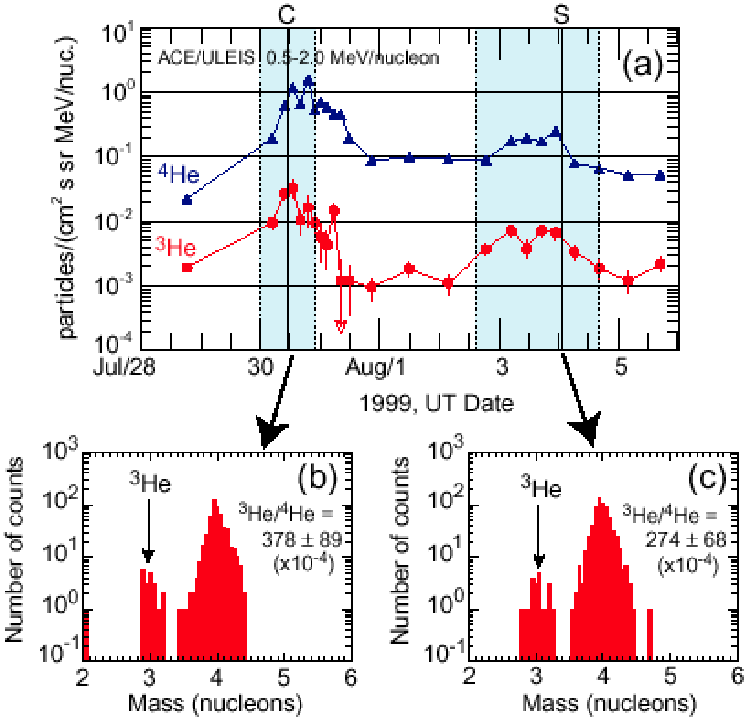


Terasawa et al. 2006

shock precursor?

complications

- both ^{3}He and ^{4}He intensities are increased at CME magnetic compression region (C) and CME fast forward shock (S)
- ^{3}He/^{4}He enhancement with respect to solar wind
- ion intensities at (C) is larger than at (S) indicates shocks are not the only acceleration mechanism in interplanetary space

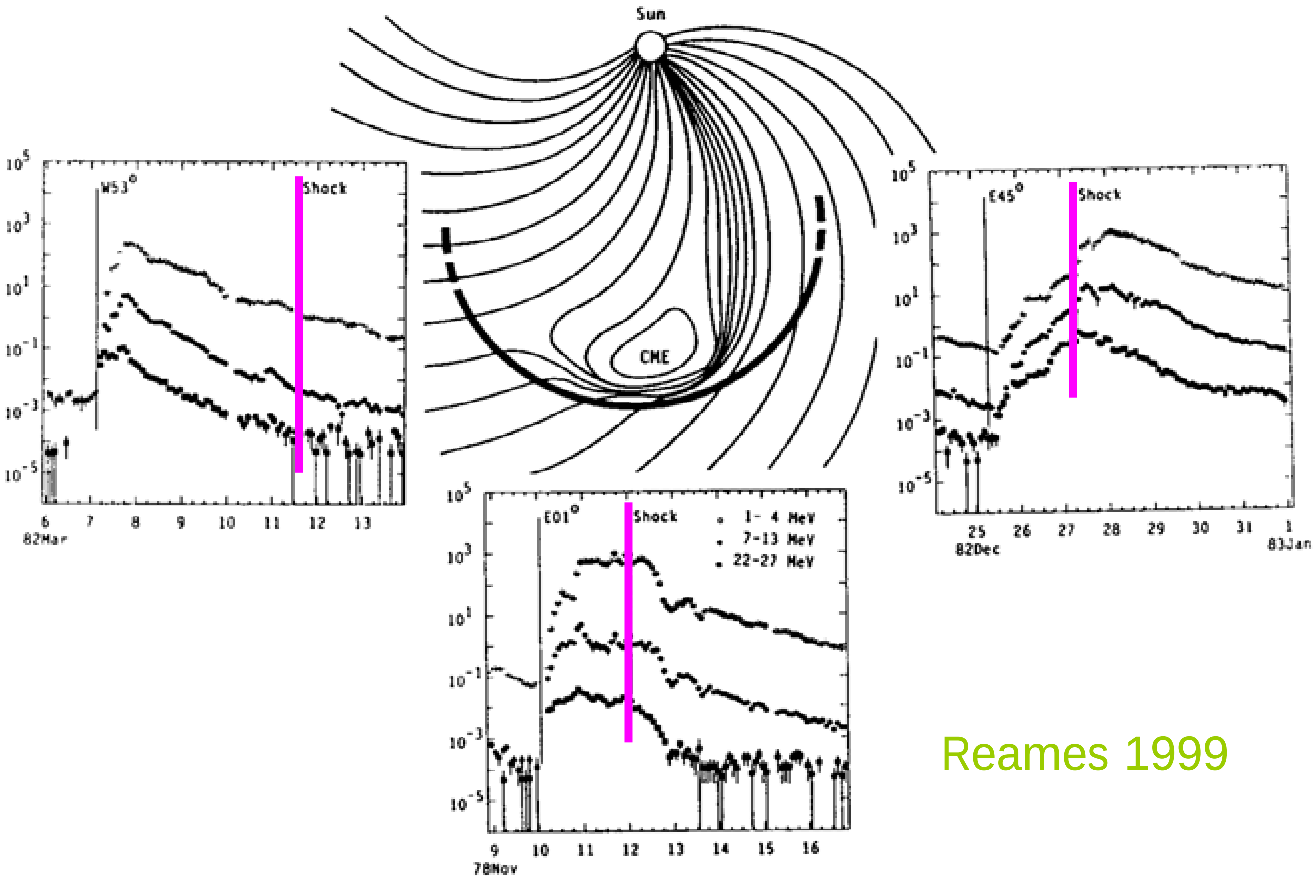


ACE news #44, 2000.04.25 (Desai et al.)

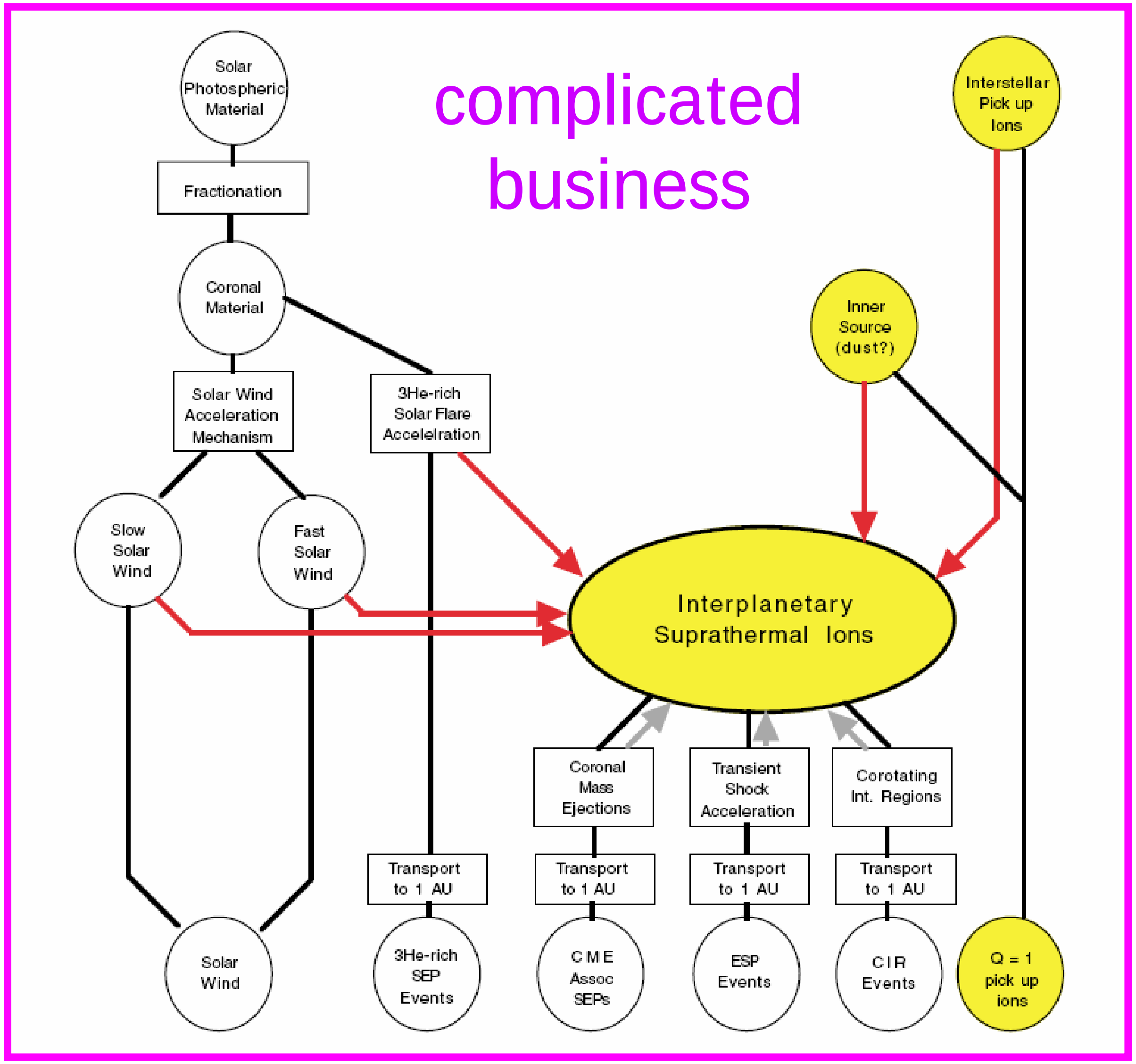
factors affecting IP shock acc

- shock strength, velocity, size and curvature, lifetime, etc.
- quasi-parallel and quasi-perpendicular
- seed populations
  - solar wind suprathermal
  - solar flare suprathermal
- CMEs may or may not have associated shocks
- direction of CMEs propagation and connectivity
- ...
- a lot of things to be disentangled

location, location, location ...
connectivity is important to interpret data
particle intensity may rise or fall after shock crossing



Reames 1999



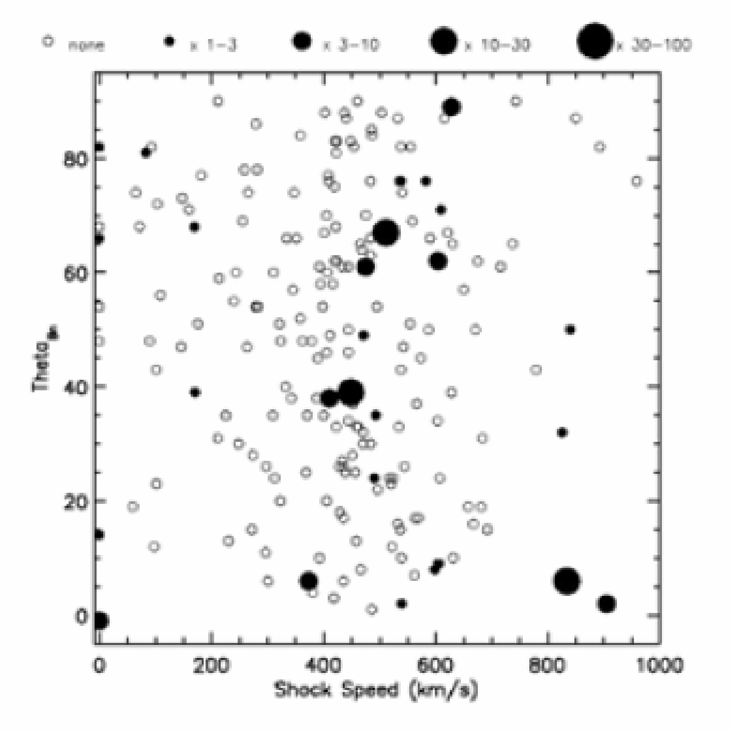
complicated business
Solar Photospheric Material
Fractionation
Coronal Material
Solar Wind Acceleration Mechanism
3He-rich Solar Flare Accelelration
Slow Solar Wind
Fast Solar Wind
Interstellar Pick up Ions
Inner Source (dust?)
Interplanetary Suprathermal Ions
Coronal Mass Ejections
Transient Shock Acceleration
Corotating Int. Regions
Transport to 1 AU
Transport to 1 AU
Transport to 1 AU
Transport to 1 AU
Solar Wind
3He-rich SEP Events
C M E Assoc SEPs
ESP Events
C I R Events
Q = 1 pick up ions

Mason 2001

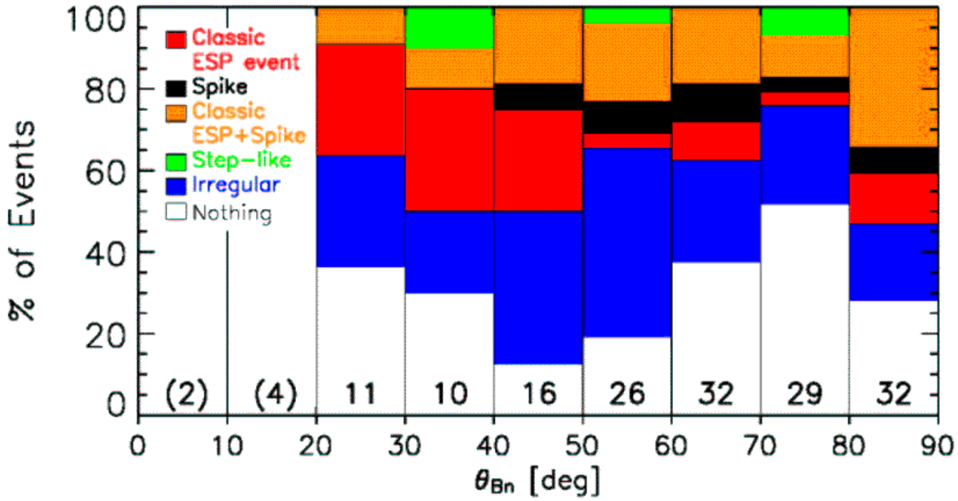
some statistics

- how does energetic particle relate to shock parameter?
- no apparent trend from shock angle and speed (except maybe shock speed has to be large enough for large increase in intensity)

354 shocks



Cohen et al. 2005



162 fast forward IP shocks (CME related)

ACE news #93, 2005.11.07 (Lario et al.)

- shock parameters may not govern the associated energetic particle event
  - maybe the energetic particle event is a history of injections and accelerations (by other shocks or accelerators), while the shock is measured locally
- about a quarter of the shocks do not affect the pre-existing particle intensities (no shock acceleration?), and another quarter of the shocks do not have obvious relation with the variation of particle intensities
  - mostly these correspond to slow and weak shocks, but also happen in a few strong shocks

cometary bow shocks or waves

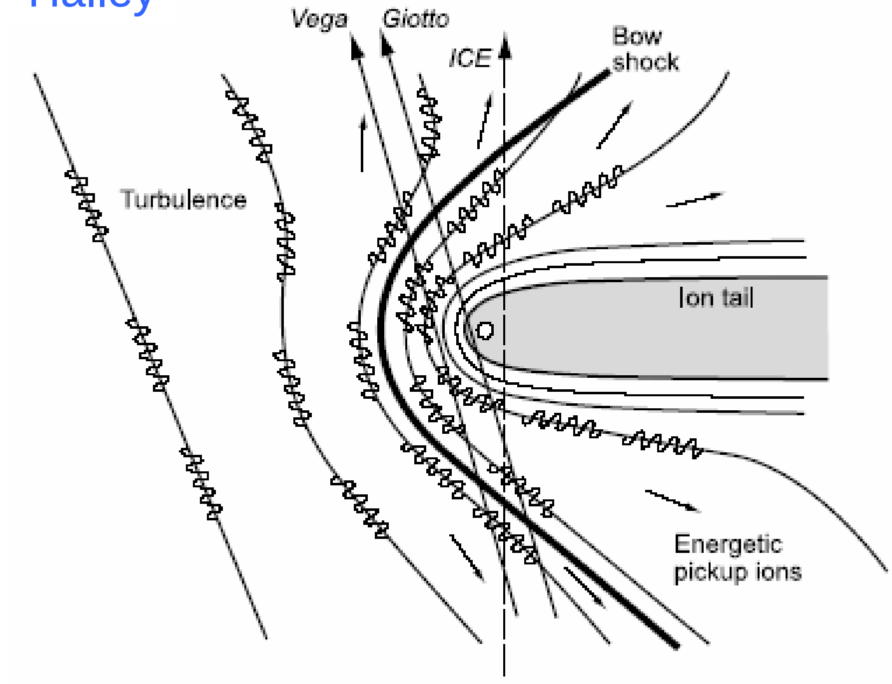
comets we have visited

Comet	Satellite	Flyby	Plasma measurement	Bow shock measurement
21P/Gaicobini-Zinner	ICE	11th Sep 1985	v	v
1P/Halley	Giotto	14th Mar 1986	v	v
26P/Grigg-Skjellerup	Giotto	10th Jul 1992	x	x
19P/Borrelly	Deep Space I	22th Sep 2001	v	v
81P/Wild 2	Stardust	2nd Jan 2004	x	x
9p/Tempel 1	Deep Impact	4th Jul 2005	x	x

cometary shock? wave?

- the vicinity of comet is very turbulent
- it is difficult to identify the bow shock (or there is no bow shock?)
- not usual foreshock waves by reflected or accelerated solar wind ions
- can associate with passage through pickup region of energetic cometary ions

Halley



Ip and Axford 1986

cometary shock? wave?

- energetic ions in extended region
  - 4 10^6 km (comparable or larger than the coma)
  - perhaps due to charge exchange again and again
- energetic ions are singly ionised ions from the water group from comet
- isotropic in pitch angle in local solar wind frame
- created far upstream then accelerated by Fermi acceleration, wave-particle interaction, pickup at higher solar wind regions, or compression of magnetic field
- second order Fermi process in action?

present status

- theoretical basis of cosmic ray acceleration is sound
- theories become very sophisticated
- but most of the time still cannot match the complications revealed by *in situ* measurements
  - shock acceleration is perhaps the major mechanism but definitely not exclusive
  - the role of geometry, temporal change, waves, pickup ions, accelerated ions, etc.

still lots of things to do
as usual

the end