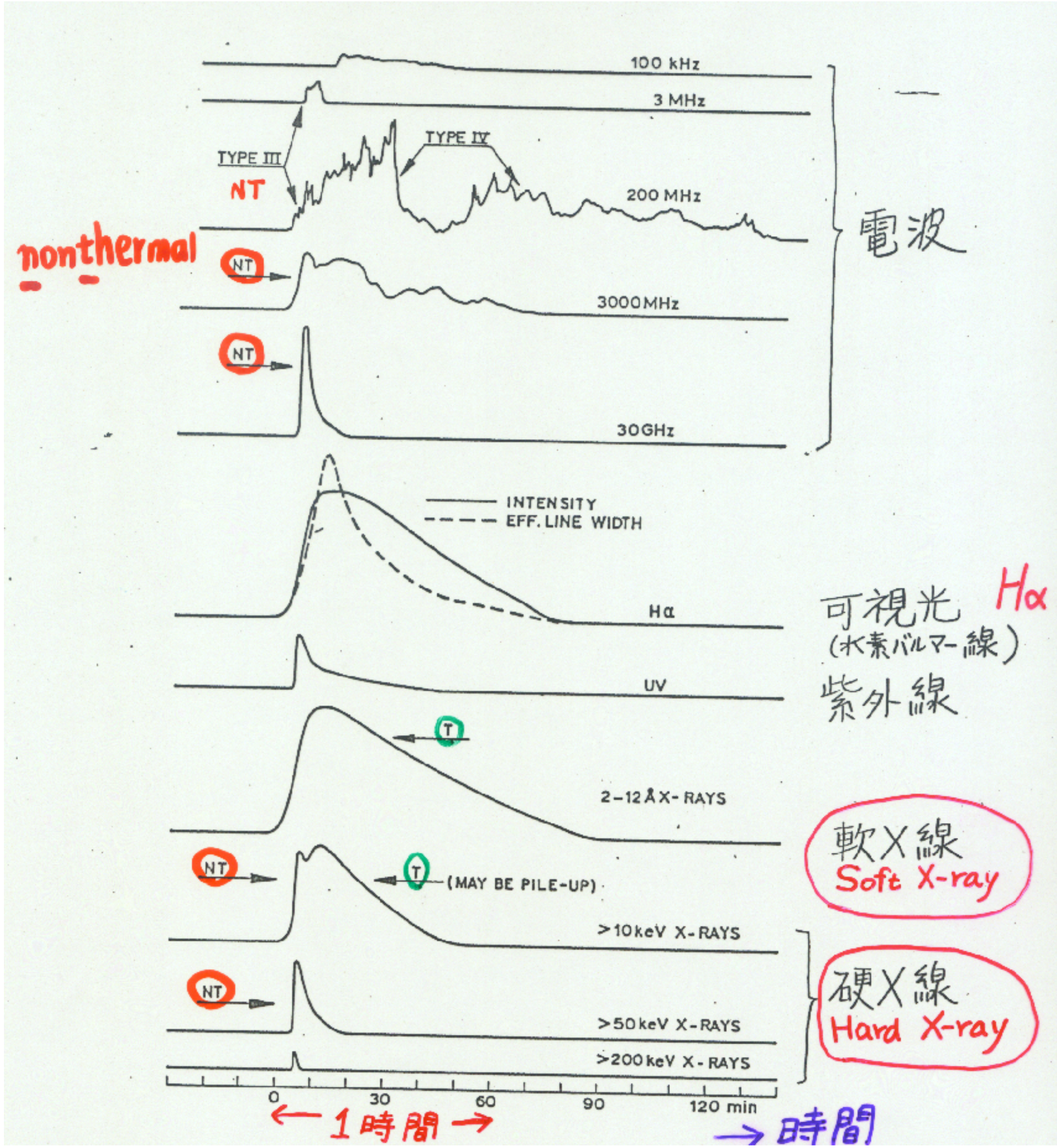
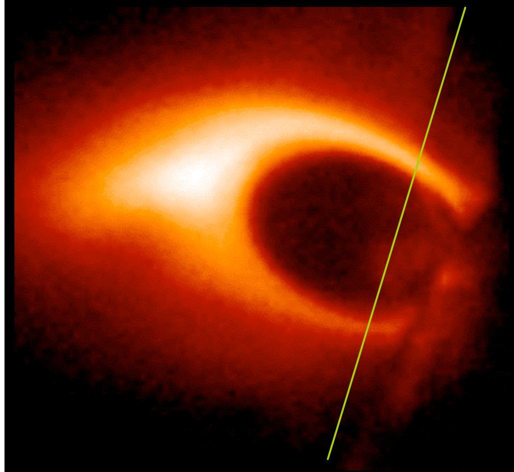
太陽における粒子加速

常田佐久
（国立天文台）

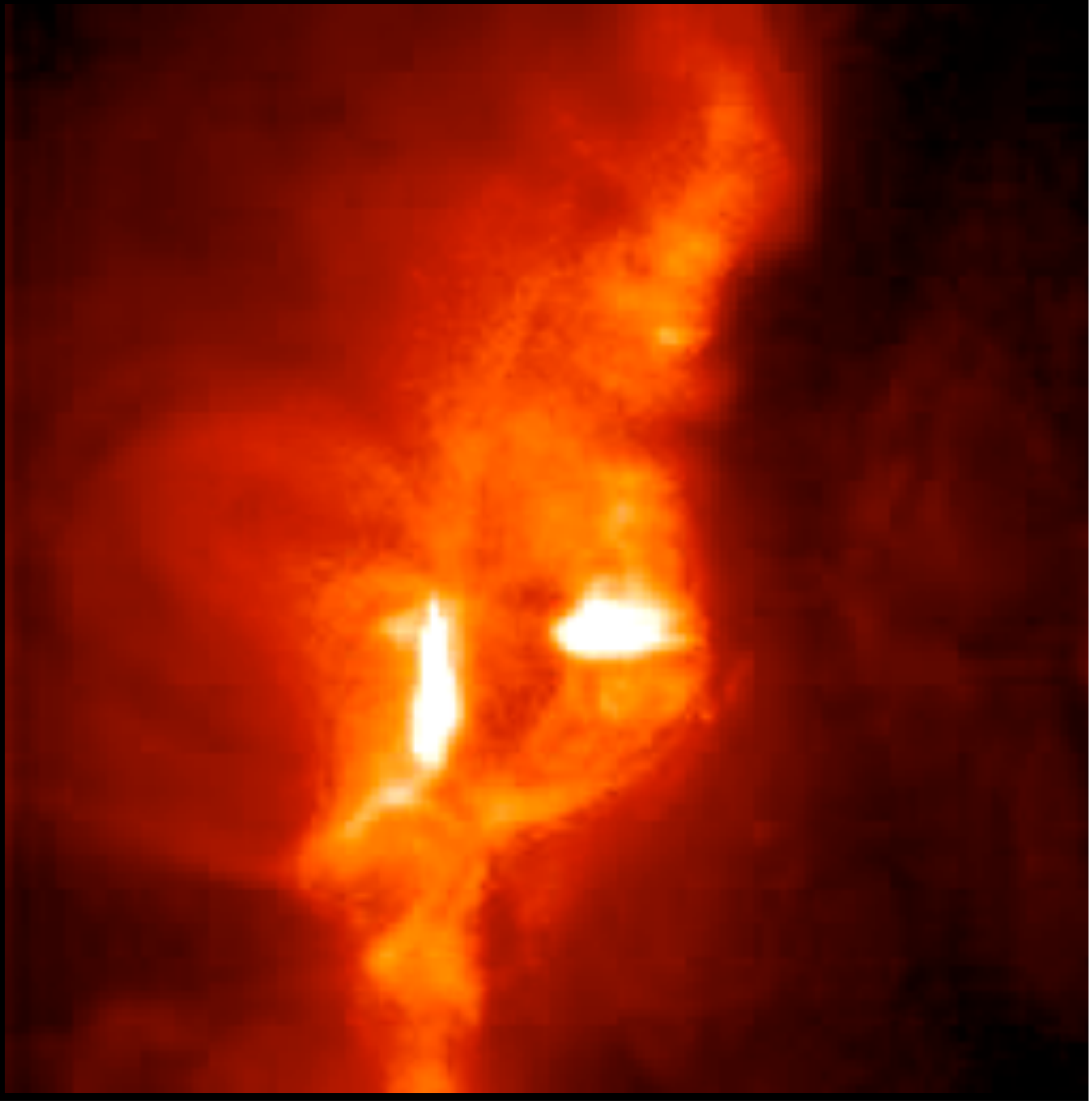
太陽フレアから放出される電磁波



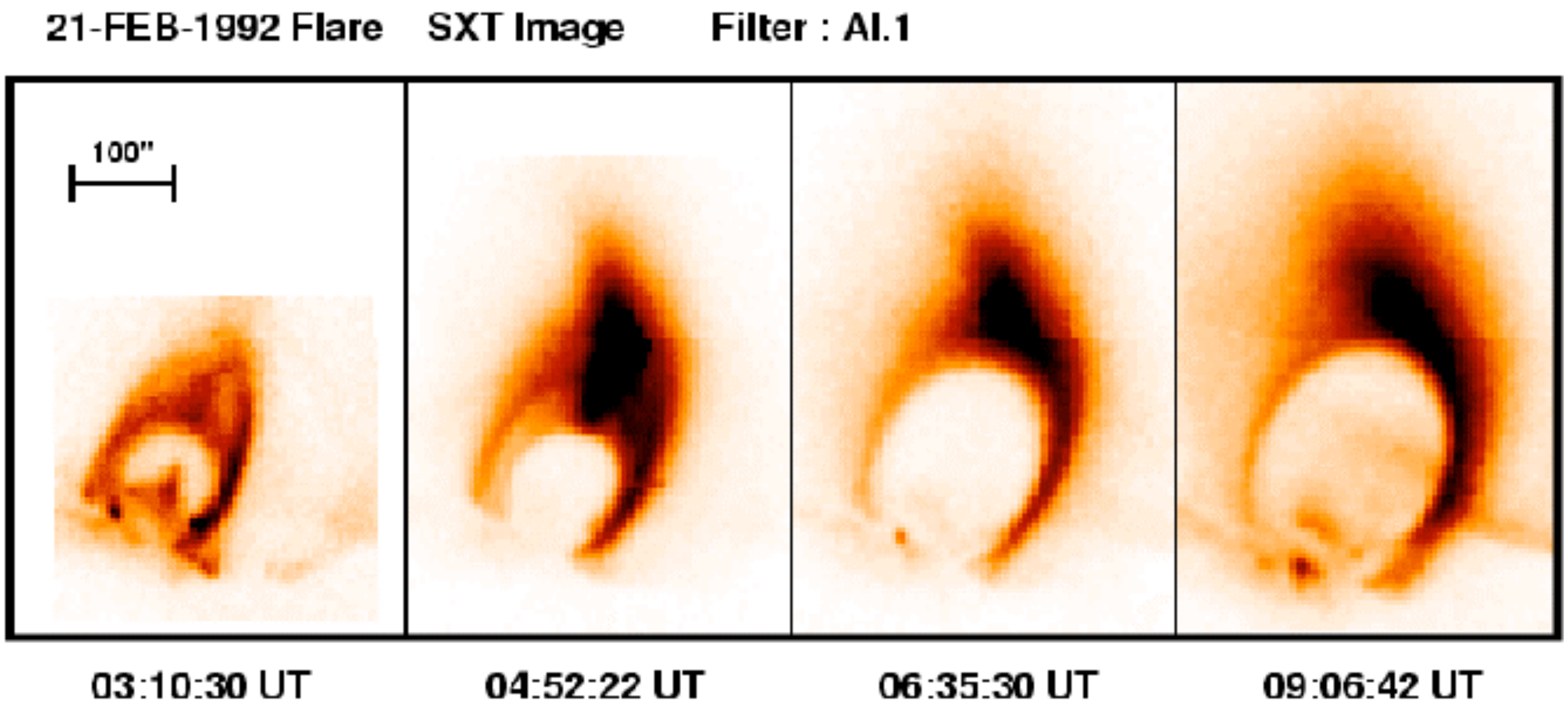
A major solar flare



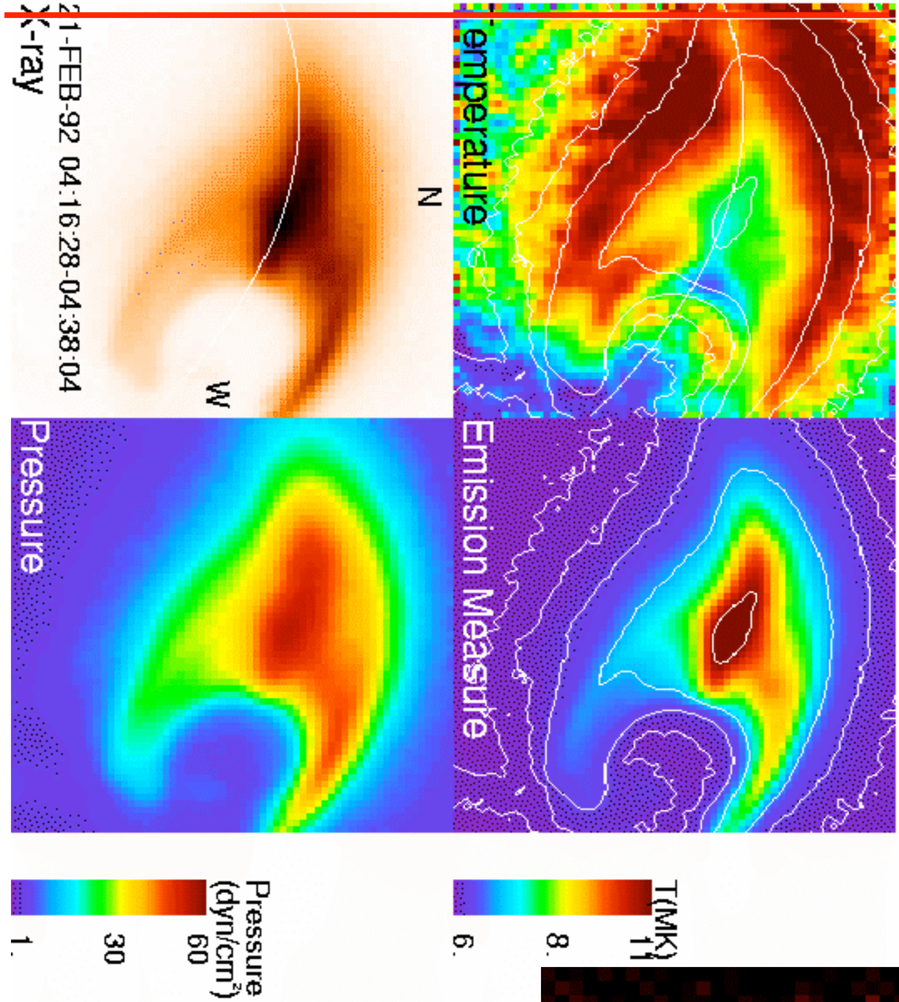
1992 Feb 21 flare



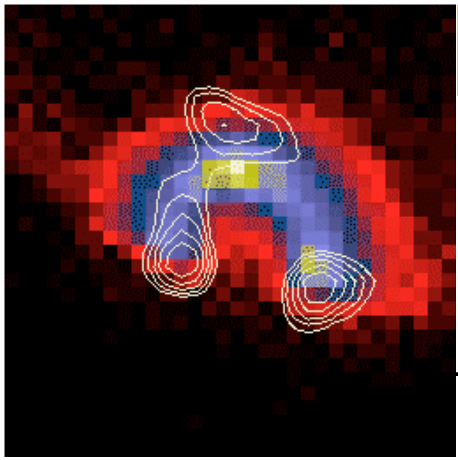
An LDE flare



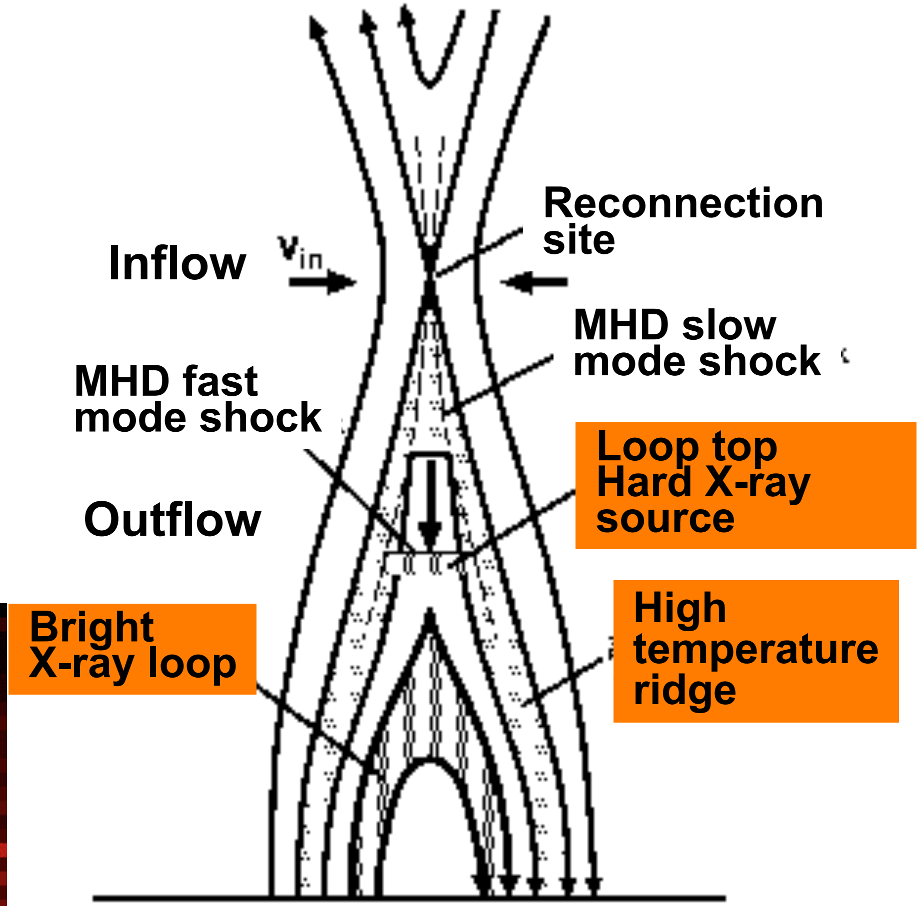
electron temperature ～10^7 K、
electron density～10^{10} cm^{-3}



High temperature ridge structure indicating concentrated line heat source (Tsuneta, ApJ, 456, 840, 1996)



100MK plasma located above the loop top

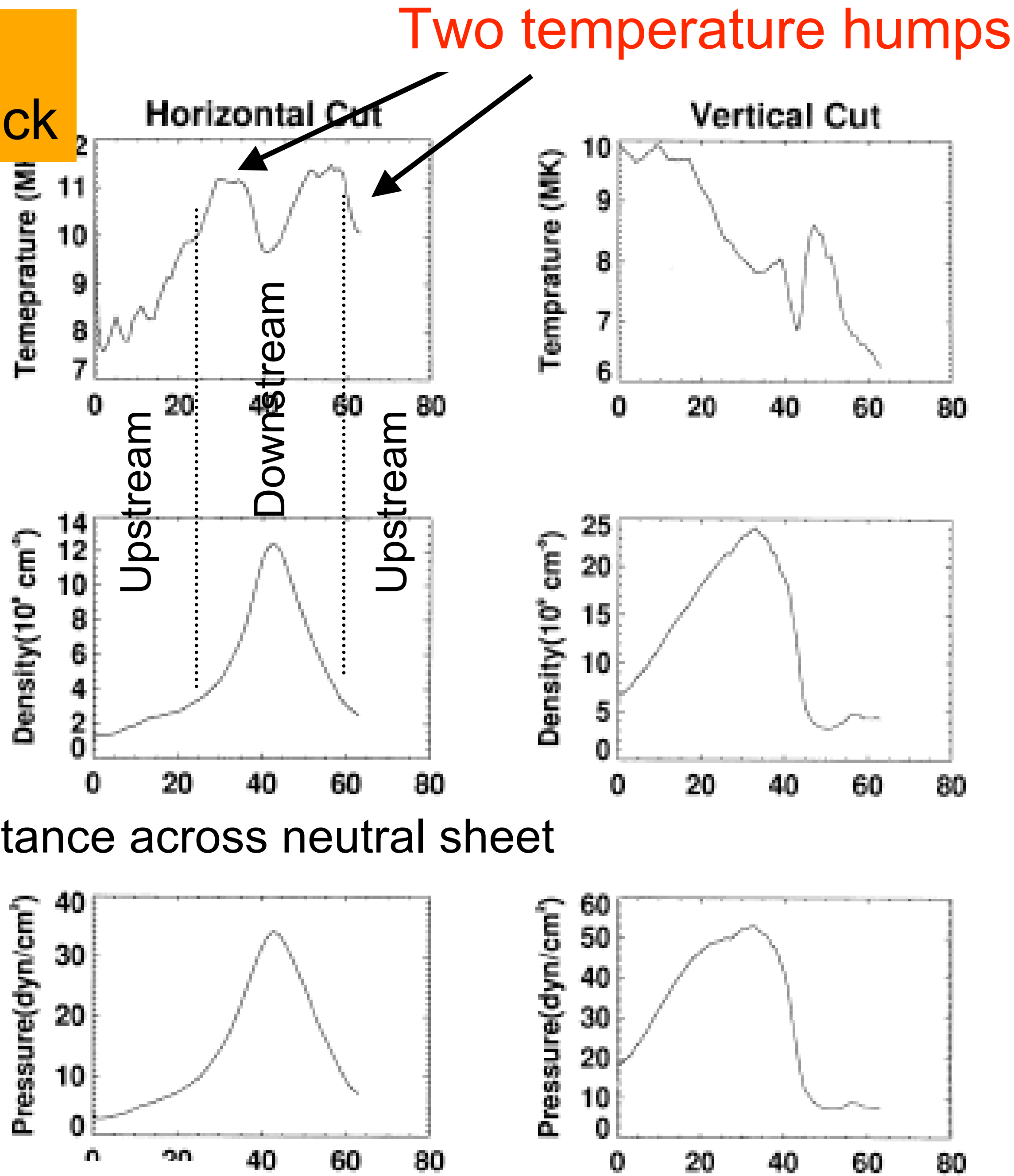


Standard 2-D picture of solar flares

Signature of slow-mode shock

Temperature

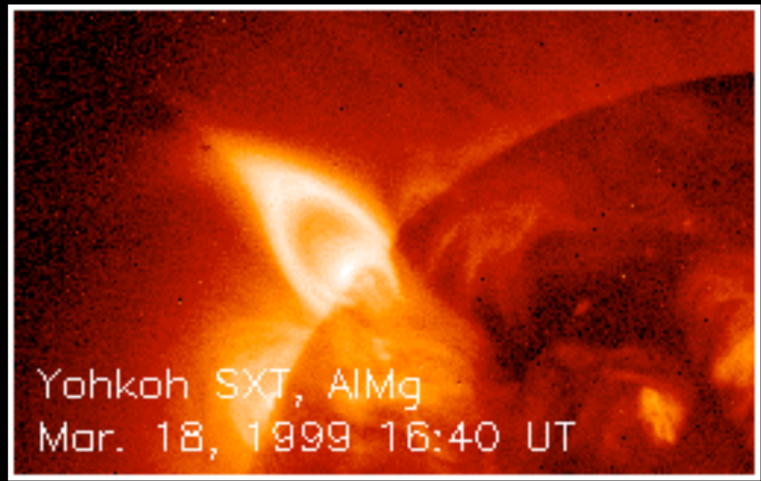
Pressure



Tsuneta, ApJ, 456, 840, 1996

Is inflow confirmed?
Discovery of Inflows with EIT

Yokoyama et al

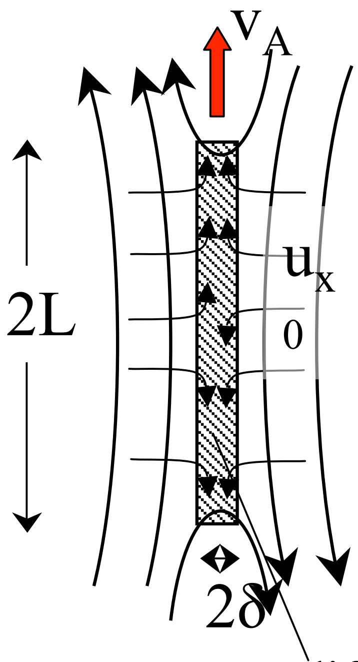


Direct observations needed with Hinode EIS/XRT

Petschek reconnection takes place

Sweet-Parker

Inflow goes through diffusion region.



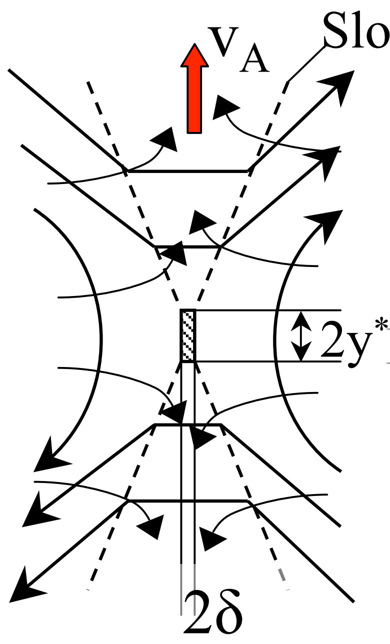
$$u_{x0} = \frac{\delta}{L} v_A = \frac{1}{\sqrt{R_m}} \sim 10^{-6} v_A$$

Very slow inflow

Too slow for solar flares

Petschek

Inflow goes through slow shock, bypassing diffusion region.



$$u_{x0} = \frac{\delta}{y^*} v_A \sim 0.01 v_A$$

Fast inflow

But,…
「ひので」でInflowもOutflowもまだ見つかっていない

Estimation of inflow speed
$0.07V_A$ (Tsuneta 1996)
$0.03V_A$ (Yokoyama 2001)

All the physical parameters are determined from observations with compressible Petschek theory（Tsuneta 1996, ApJ)

Reconnection outflow領域
Alfven Mach数～5
Acoustic Mach数～1

TABLE 1

PHYSICAL PARAMETERS OF UPSTREAM/DOWNSTREAM OF THE MAGNETIC SEPARATRIX LINES AND SLOW SHOCK

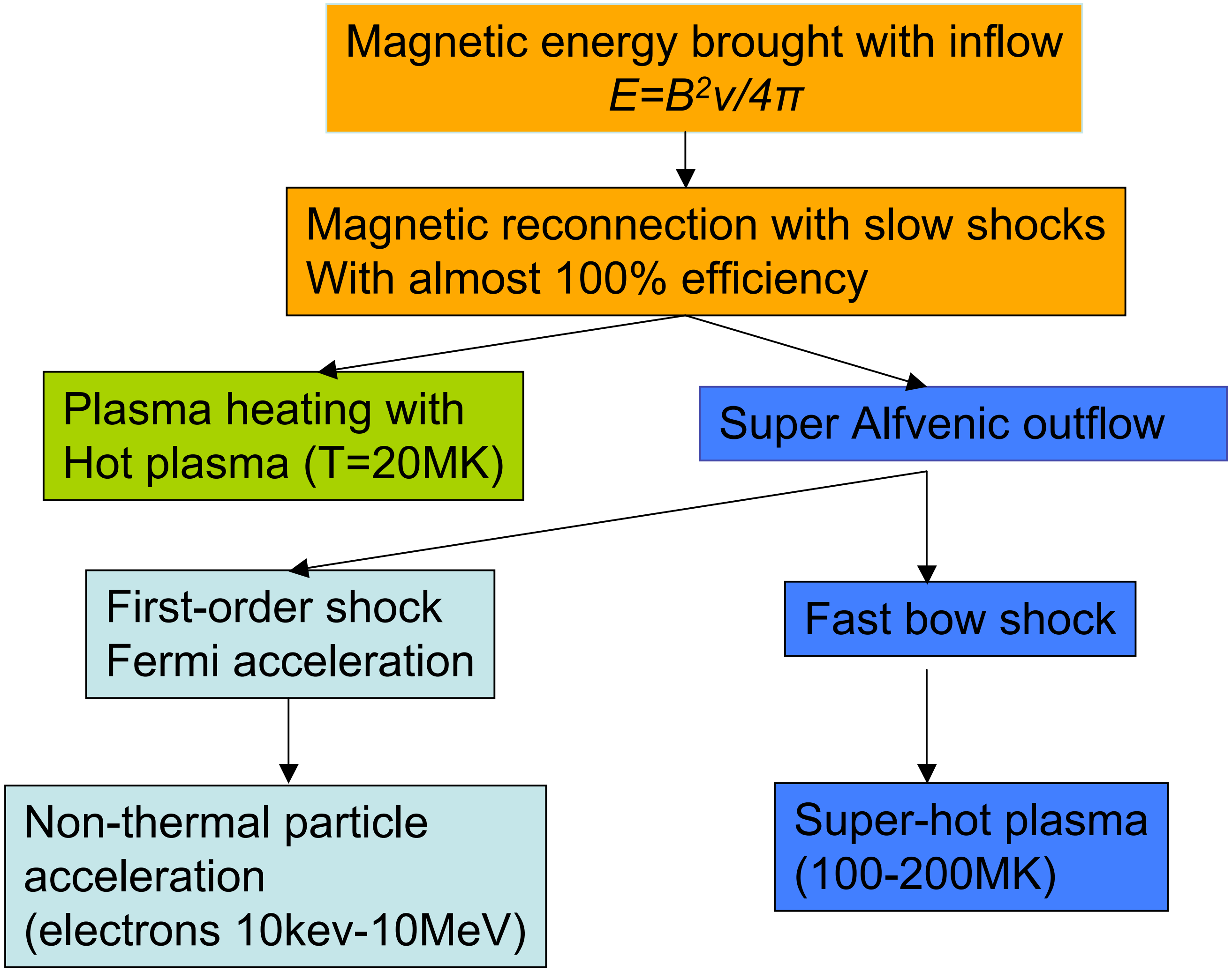
Parameter	Upstream	Downstream
Temperature	<7 MK	>12–13 MK
Density	10^9 cm^{-3}	<5 × 10^9 cm^{-3}
Pressure	3 dyn cm^{-2}	<20 dyn cm^{-2}
Magnetic field	20–30 G	5 G
Plasma β	~0.25	~30
Flow velocity	56 km s^{-1}	800 km s^{-1}
Sound Mach number	~0.1	~1
Alfvén Mach number	~0.07	~5
Alfvén speed	800 km s^{-1}	155 km s^{-1}
Sound speed	550 km s^{-1}	770 km s^{-1}
Mass flux	~1.7 × 10^{35} s^{-1}	~2.4 × 10^{35} s^{-1}

TABLE 2

PHYSICAL PARAMETERS OF THE RECONNECTION REGION

Parameter	Value
Cool channel temperature	10–6 MK
Cool channel density	5–25 × 10^9 cm^{-3}
Cool channel pressure	20–50 dyn cm^{-2}
Density jump across the slow shock	<5
Temperature jump across the slow shock	~1 (γ ~ 1)
Half-angle of the slow shocks	0°8–1°8
Half-angle of the separatrices	5°–11°
Kinetic energy of the outflow	5 × 10^{27} ergs s^{-1}
Shock heating rate	9 × 10^{27} ergs s^{-1}
Total energy	14 × 10^{27} ergs s^{-1}
Magnetic energy supply from the upstream	6 × 10^{27} ergs s^{-1}
Soft X-ray loop height	~6 × 10^4 km
X-point height	~14–24 × 10^4 km above the photosphere ~8–18 × 10^4 km above the loop top
Slow shock length	~a few × 10^4 km

Magnetic reconnection highly efficient engine based on the analysis of 1992 Feb 21 flare



Energy budget in solar flares

- Total energy of the system
  - $L=5x10^4$km、B=200G

$$E = L^3 \cdot B^2/8\pi \approx 10^{32}\ \mathrm{erg}$$

- Energy rate
  - Inflow speed is approx. ***7% of Alfven velocity（α=0.07）***

$$E = \alpha V_A \cdot L^2 \cdot B^2/4\pi = 10^{30}\ \mathrm{erg/sec}$$

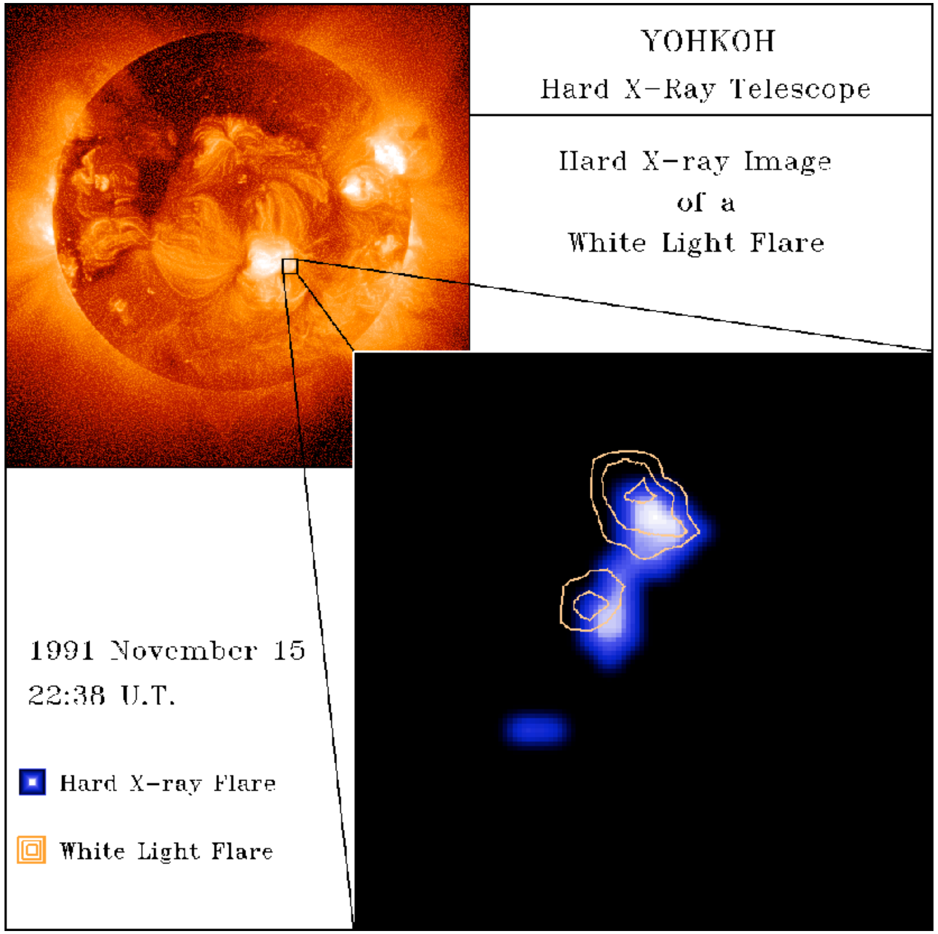
- Magnetic reconnection is extremely efficient（～100%） cosmic engine.

Yohkoh founds

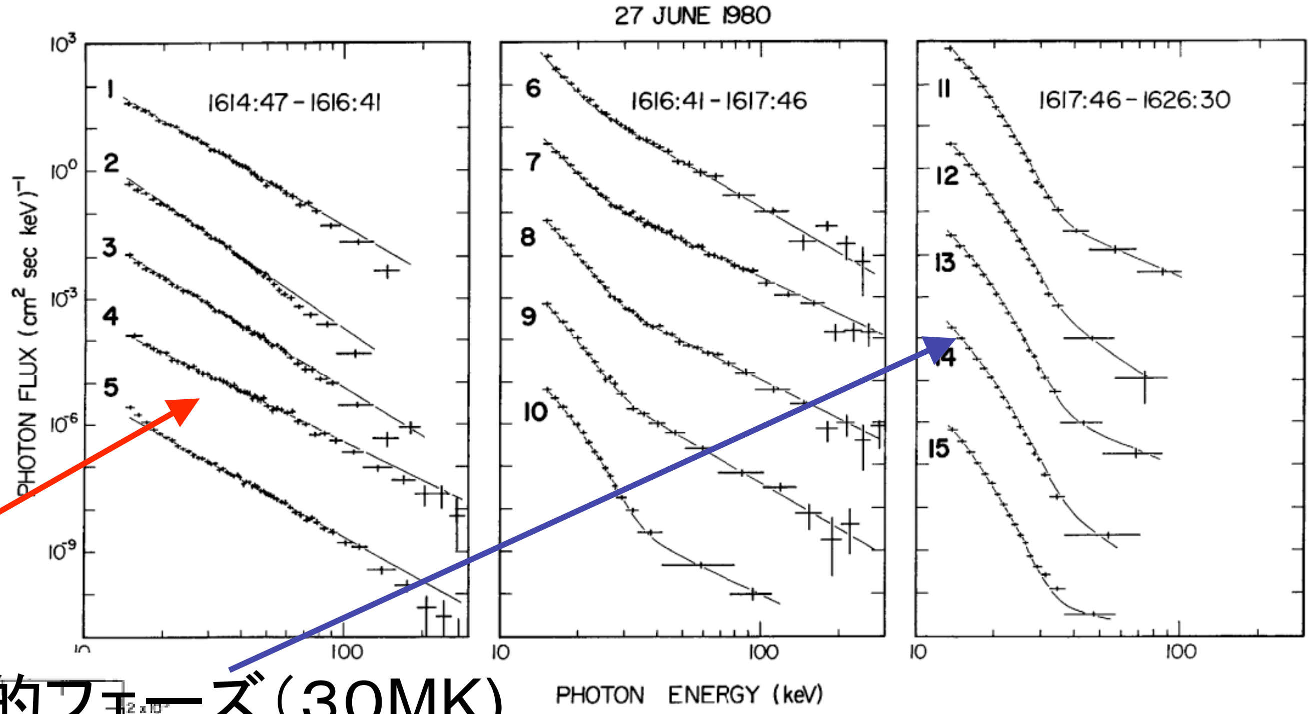
- All the transients heating is due to magnetic reconnection.
- Slow shock plays a key role, and very efficient energy conversion is going on with reconnection.
- Fast outflow is evidenced by superhot source seen in hard X-rays.
- Inflow is observed, and the speed is consistent with estimation.
- Particle acceleration takes place in outflow and fast shock region.

硬X線フレア

- エネルギー ：10^{29}-10^{32}エルグ
- 時間スケール：数10秒 – 1時間
- ほとんどの場合、2つ目玉構造をしている（電子が光速近くまで加速され、彩層に衝突し制動放射で硬X線を出す）。
- 陽子も加速される場合がある。



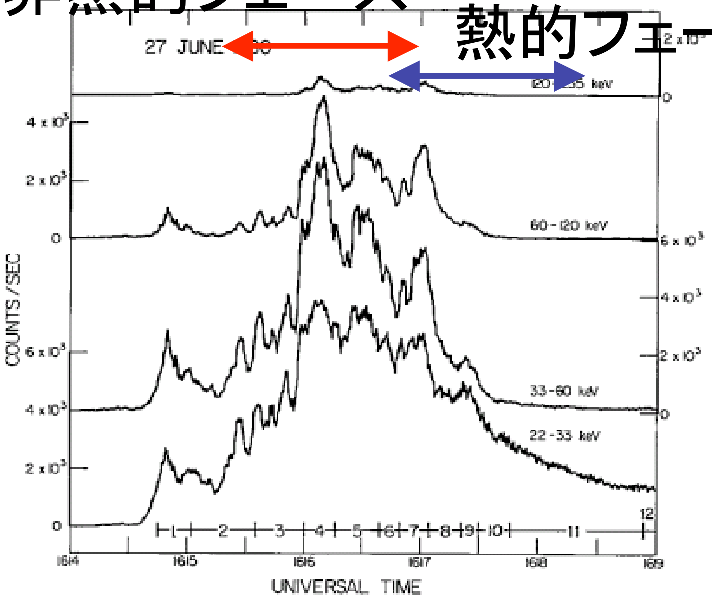
フレアの時間的進化：加速から加熱へ



rom the germanium array through the event. The vertical scale applies to the uppermost spectrum, with each succeeding spectrum offset downward by two

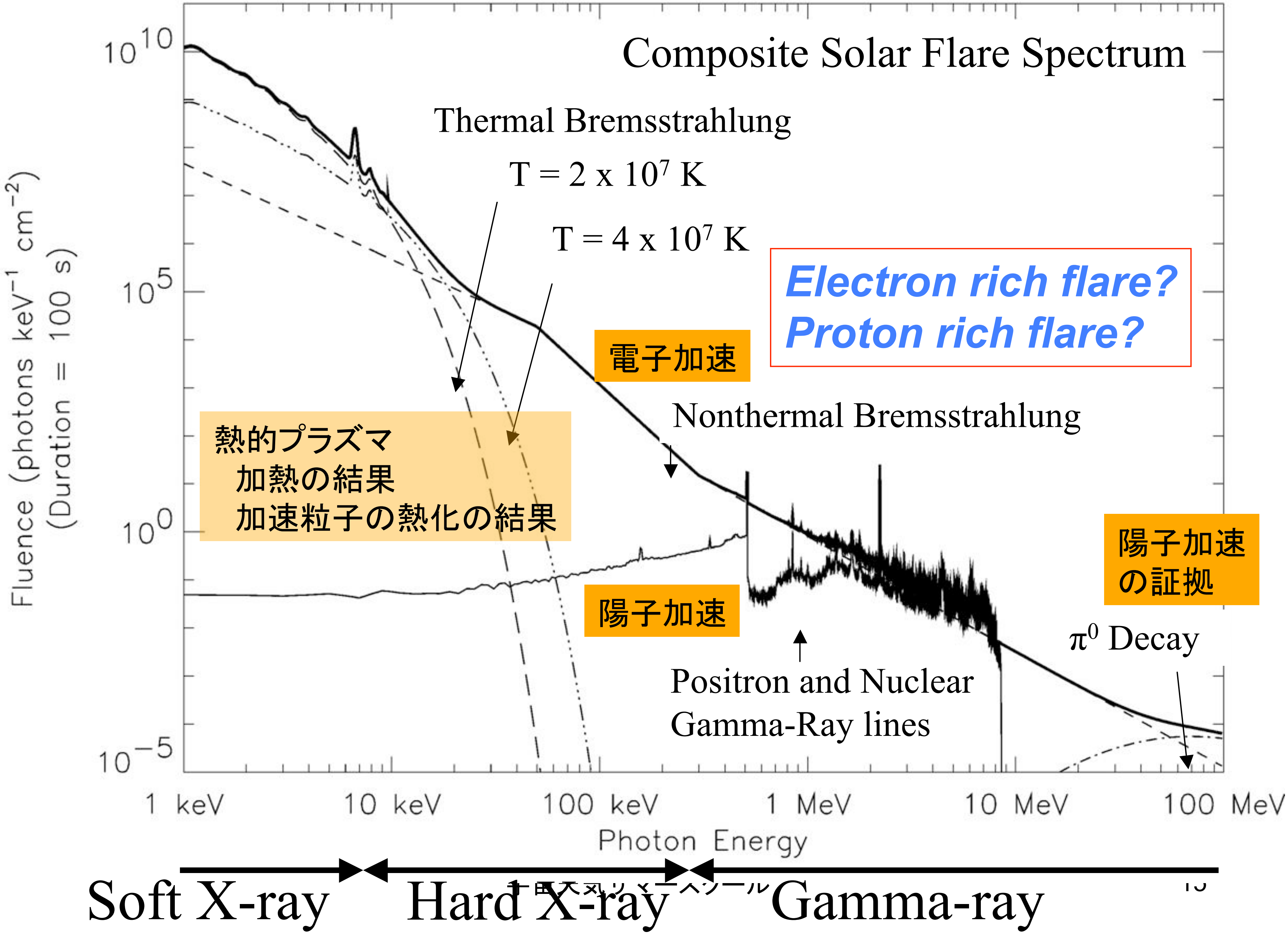
非熱的フェーズ

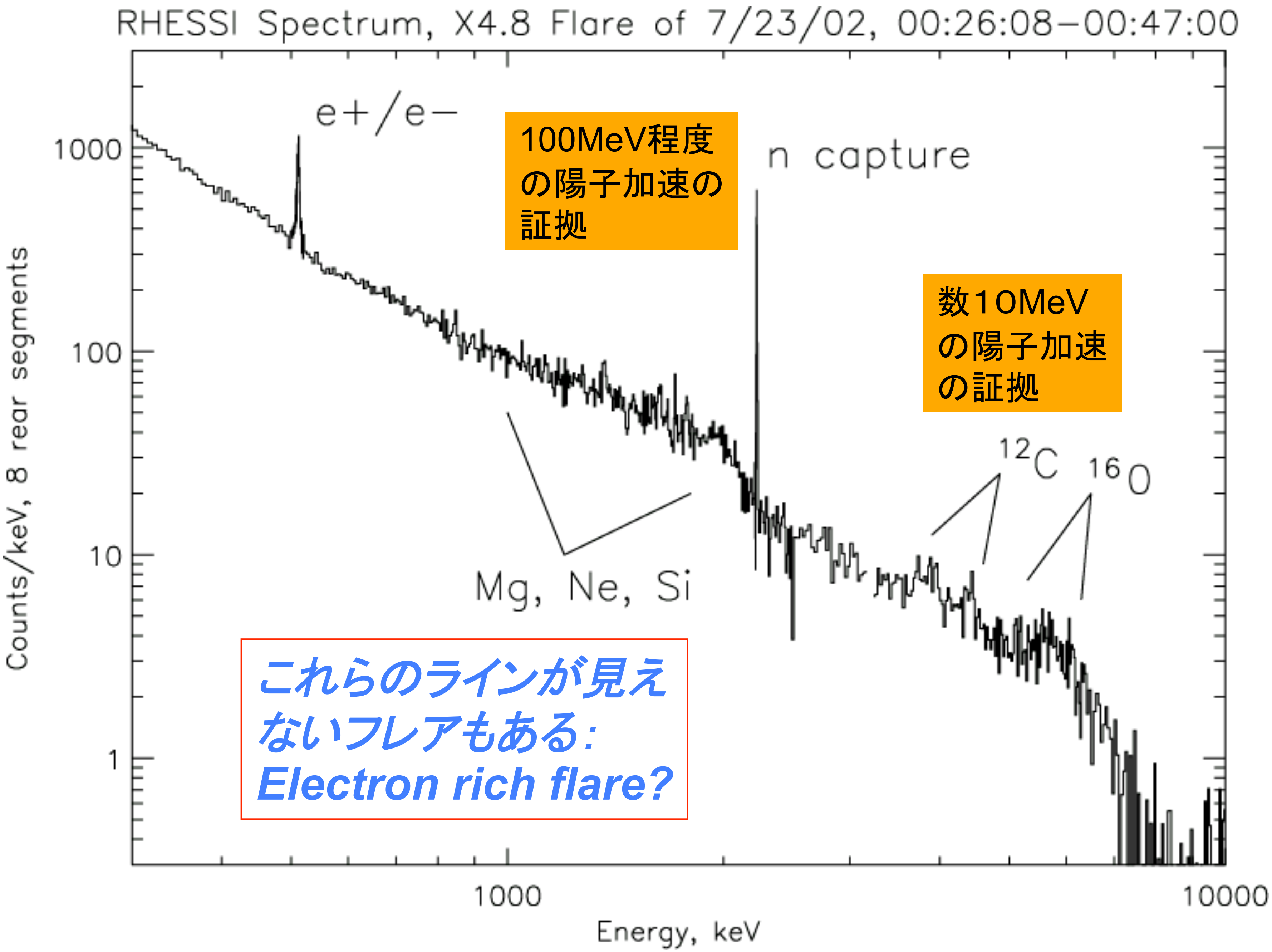
熱的フェーズ（30MK）



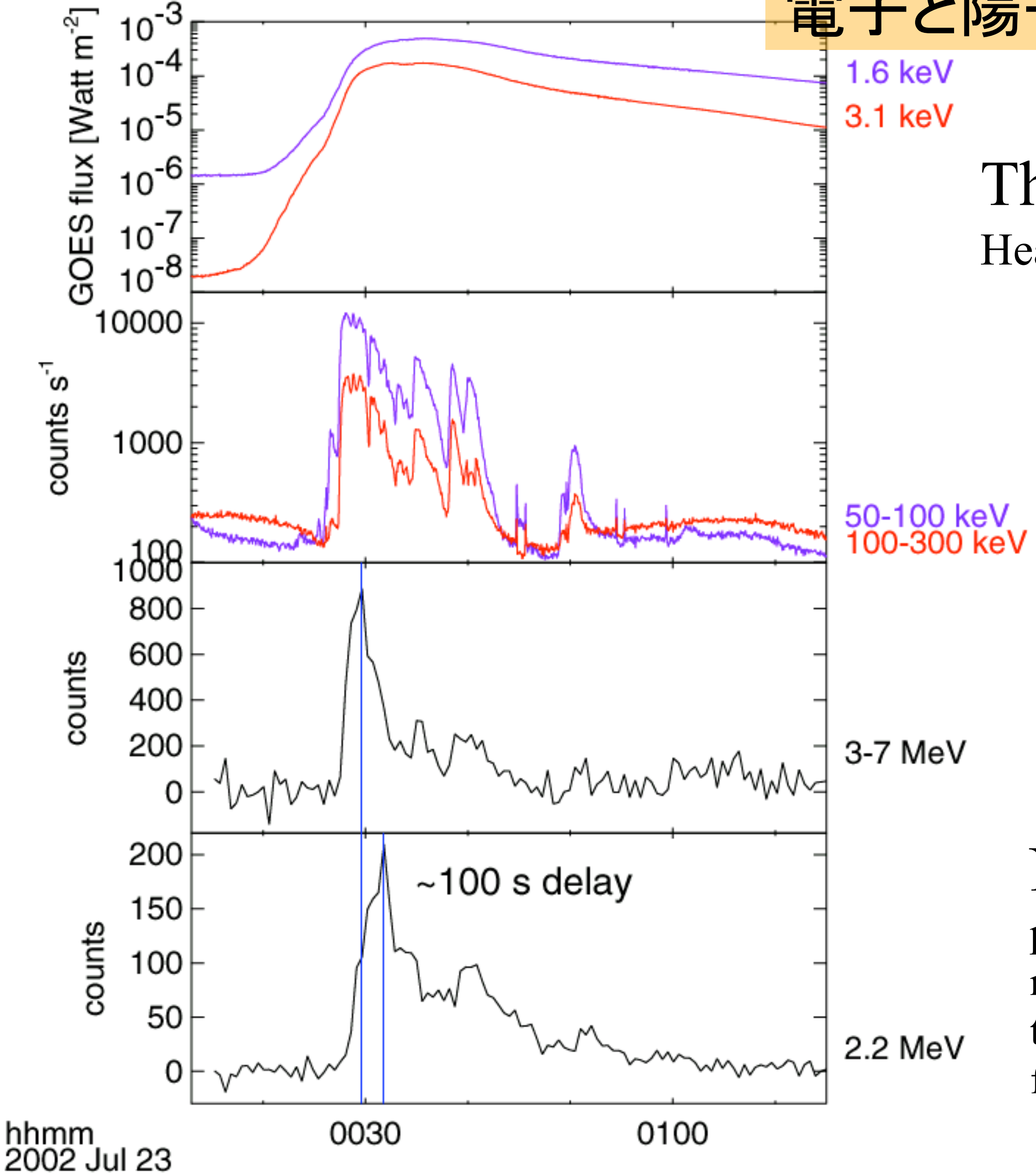
初期(粒子加速が起きている)
- 硬いX線強度の激しい時間変化
- べき型スペクトル

後期(粒子加速が停止し強い加熱)
- なだらかな時間変化
- 熱的スペクトル


Composite Solar Flare Spectrum
Thermal Bremsstrahlung
T = 2 x 10^7 K
T = 4 x 10^7 K
Electron rich flare?
Proton rich flare?
電子加速
Nonthermal Bremsstrahlung
熱的プラズマ
加熱の結果
加速粒子の熱化の結果
陽子加速
Positron and Nuclear
Gamma-Ray lines
陽子加速
の証拠
π^0 Decay
Fluence (photons keV^-1 cm^-2)
(Duration = 100 s)
10^10
10^5
10^0
10^-5
1 keV
10 keV
100 keV
1 MeV
10 MeV
100 MeV
Photon Energy
Soft X-ray
Hard X-ray
Gamma-ray


RHESSI Spectrum, X4.8 Flare of 7/23/02, 00:26:08–00:47:00
e+/e−
100MeV程度の陽子加速の証拠
n capture
数10MeVの陽子加速の証拠
^{12}C
^{16}O
Mg, Ne, Si
これらのラインが見えないフレアもある:
Electron rich flare?
Counts/keV, 8 rear segments
Energy, keV
1000
100
10
1
1000
10000

電子と陽子はほぼ同時に加速



Thermal (SXR):

Heated plasma

non-thermal (HXR):

Bremsstrahlung of energetic electrons at footpoints

Prompt lines:

De-exitation lines (C and O) accounts for 60%, the rest is electron bremsstrahlung

Neutron capture line:

p hit heavier nuclei producing neutrons. Neutrons slow down, then captured by ambient hydrogen forming deuterium + 2.2 MeV.

加速と加熱

- 加熱に分類
  - 分布関数はMaxwell:Te=Ti
  - 分布関数はMaxwell:Te＞Ti、Te<Ti
    - トランジエント加熱(フレア）では電子温度とイオン温度は一致していないだろう。
    - 比較的長い緩和時間（分のオーダー）のあとTe=Tiとなる。
  - 分布関数はMaxwellでないが、バルク加熱
- 加速
  - 電子、陽子の一部を選択的に加速。一般に加速粒子の等価温度は、背景プラズマのそれを大きく上回る。
- 加速と加熱の中間領域はありえる。

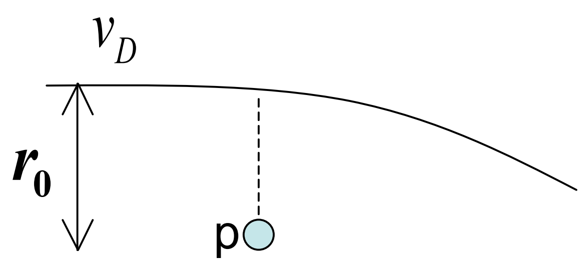
Four conditions that any theory in electron acceleration should meet

- *Maximum energy*
  - 100keV～10MeV
  - Background plasma temperature is 0.1-0.3keV, and a factor of 10^3～10^5 in energy is needed.
- *Initial acceleration from thermal pool*
  - Acceleration has to win against collisional drag force.
- *Acceleration time*
  - 1 second to accelerate to 100keV-1MeV
  - Note that Aflven time scale is given by L/V_A ～ 10～100sec （$L=10^{4-5}$Km）
  - Since inflow speed is about 7％ of the upstream Alfven speed, the duration of flares is $L/\alpha V_A$～100-1000 seconds
  - Acceleration time scale of 1 second indicates the size of $L=10^3$Km
- *Number of accelerated electrons*
  - 10^{33-35} /sec
  - Assuming the size of the acceleration site $L=10^4$Km, 10% of background electrons have to runaway

電場による粒子加速

Dreicer field： electronがrun-away する電場強度E_D

$$m\dot{v}_D = -eE - m v_D \nu_{ei}(v) \quad (e>0)$$



Large angle collision

$$F = \frac{e^2}{4\pi\varepsilon_0 r_0^2} \qquad \Delta T = \frac{r_0}{v} \qquad \Delta(mv) \approx mv = F\Delta T$$

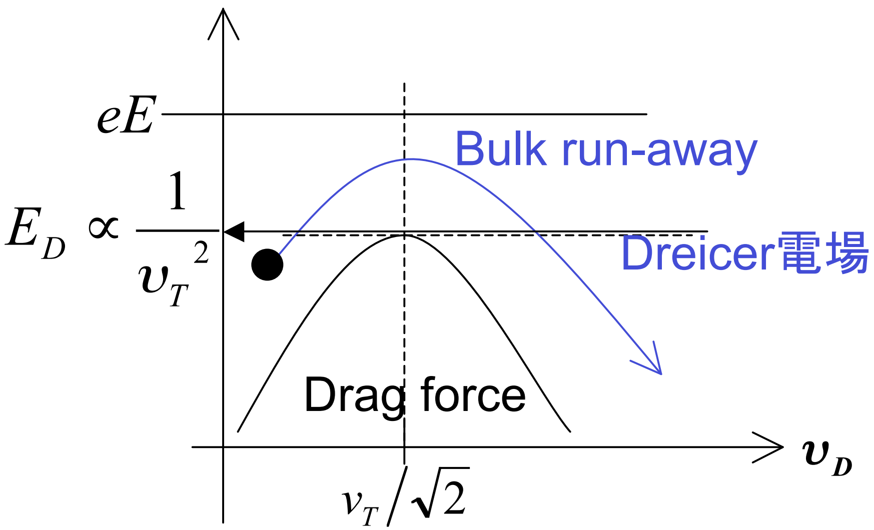
$$\sigma = \pi r_0^2 = \frac{e^4}{16\pi\varepsilon_0^2 m_e^2 v^4} \qquad \nu_{ei} = nv\sigma = \frac{ne^4}{16\pi\varepsilon_0^2 m_e^2 v^3}\ln\Lambda$$

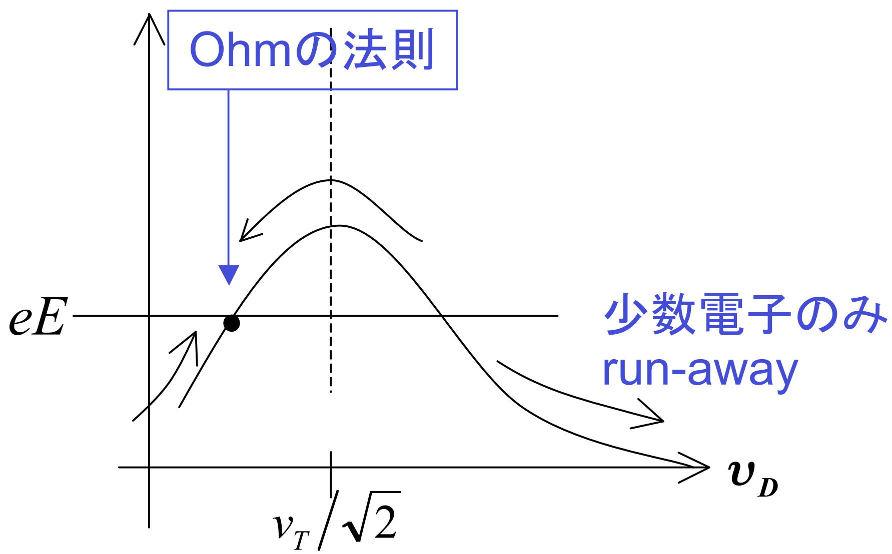
Includes small angle collision

$$Drag = -m v_D \upsilon(v\ ) = -\frac{ne^4 \ln\Lambda}{16\pi\varepsilon_0^2 m}\frac{v_D}{(v_D^2 + v_T^2)^{1.5}}$$

V_D: test particle v_T: thermal speed

E_D: Dreicer 場（全粒子がrun-awayする電場の強さ）





E_D: Dreicer 場
（全粒子がrun-awayする電場の強さ）

$$eE_D = \frac{ne^4 \ln\Lambda}{16\pi\varepsilon_0^2 m v_T^2}$$

$$E_D[V/cm] = 1.9\times10^{-16}\frac{n[cm^{-3}]}{T[keV]}\ln\Lambda$$

$$T = 2keV, n \approx 10^{11} cm^{-3}$$

$$E_D = 2\times10^{-2} V/m$$

$$\ln\Lambda = 20$$

$$l = 10^5 km = 10^8 m$$

runaway粒子数の計算 Kruskal and Bernstein 1964

$$n_r = 0.35 n_0(\mathrm{cm}^{-3}) \nu_{\mathrm{eff}}(\mathrm{s}^{-1}) \epsilon^{-3/8} \exp\ f(\epsilon)\ \mathrm{s}^{-1}\ \mathrm{cm}^{-3}$$

$$f(\epsilon) = -\left(\frac{2}{\epsilon}\right)^{0.5} - \frac{1}{4\epsilon} .$$

$$\varepsilon = E / E_D$$

εが求まれば、ruaway粒子数が評価できる(Tsuneta 1985)。ε～0.1-0.3でフレアの加速電子数を説明。ただし、電流密度が大きすぎ、打ち消すためリターン電流が必要。

加速された粒子のスペクトルを求める

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial E}\left(\frac{dE}{dt}N\right) = q - \frac{N}{\tau}$$

$$\frac{dE}{dt} = \left.\frac{dE}{dt}\right|_{加速} - \left.\frac{dE}{dt}\right|_{loss}$$

エネルギー空間中での質量保存の式

類推

$$\frac{\partial n}{\partial t} + \nabla \cdot \vec{F} = q - \frac{n}{\tau}$$

$$\vec{F} = n\vec{v} + D\nabla n$$

質量保存の式

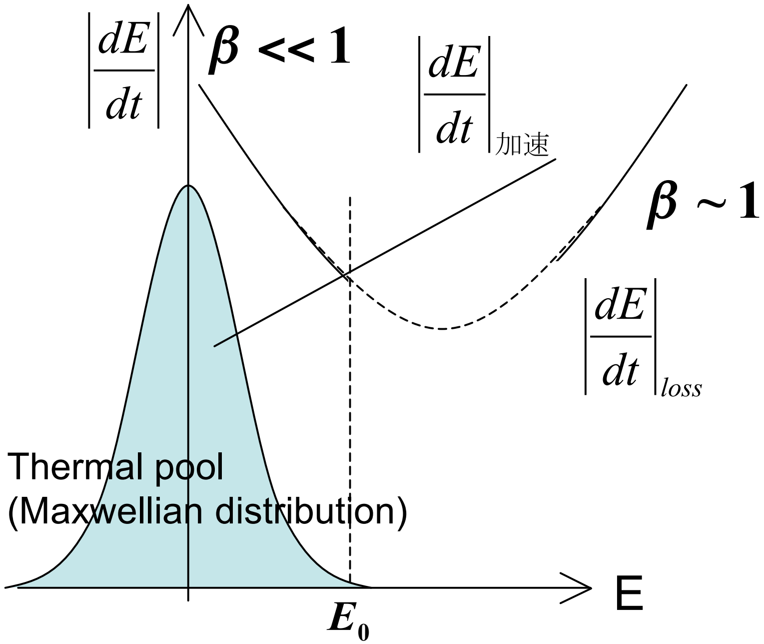
大事なロスターム〔電子の場合〕

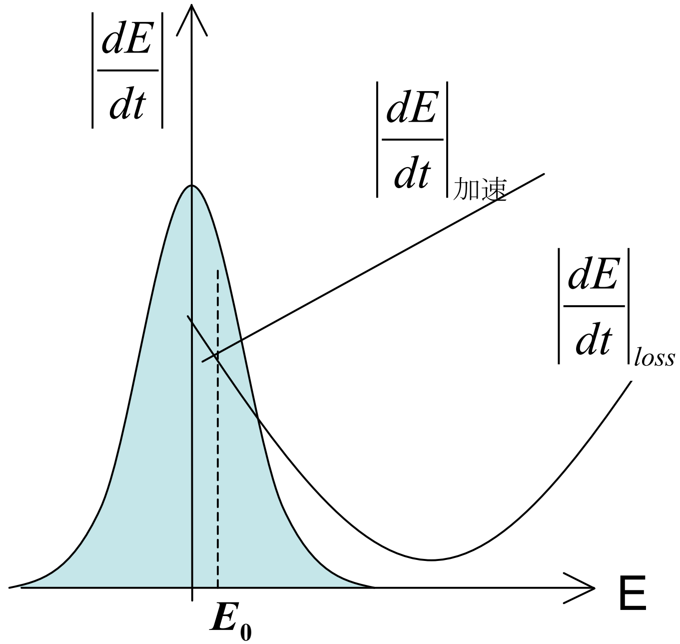
$$\left.\frac{dE}{dt}\right|_{loss} = 4.9\times 10^{-9} n[cm^{-3}]E[keV]^{-0.5}[keV/s]$$

for $\beta \equiv \frac{v}{c} << 1$ (electron collision loss)

$$\left.\frac{dE}{dt}\right|_{loss} \propto E^2 (\beta \approx 1) \quad \text{(synchrotron loss)}$$

粒子加速のinjection問題（その１）





粒子を別のメカニズムにより$E=E_0$まで持上げあげる必要がある

粒子をthermal poolから直接加速できる

$$E < E_0 \quad \left.\frac{dE}{dt}\right|_{加速} < \left.\frac{dE}{dt}\right|_{loss}$$

$$E = E_0 \quad \left.\frac{dE}{dt}\right|_{加速} = \left.\frac{dE}{dt}\right|_{loss}$$

$$E > E_0 \quad \left.\frac{dE}{dt}\right|_{加速} > \left.\frac{dE}{dt}\right|_{loss}$$

$$\frac{d}{dE}\left(\left.\frac{dE}{dt}\right|_{加速} N\right) + \frac{N}{\tau} = 0 \qquad \frac{\partial N}{\partial t} \equiv 0 \quad q = 0$$

電場加速の場合、以降: E→εと書く。

$$m\frac{dv}{dt} = +eE \quad (E > E_D) \quad (e < 0) \quad (\text{衝突項なし})$$

運動方程式から加速レートは、

$$\frac{d\varepsilon}{dt} = +\sqrt{\frac{2}{m}} eE\varepsilon^{1/2}$$

加速時間は、

$$\varepsilon \propto t^2$$

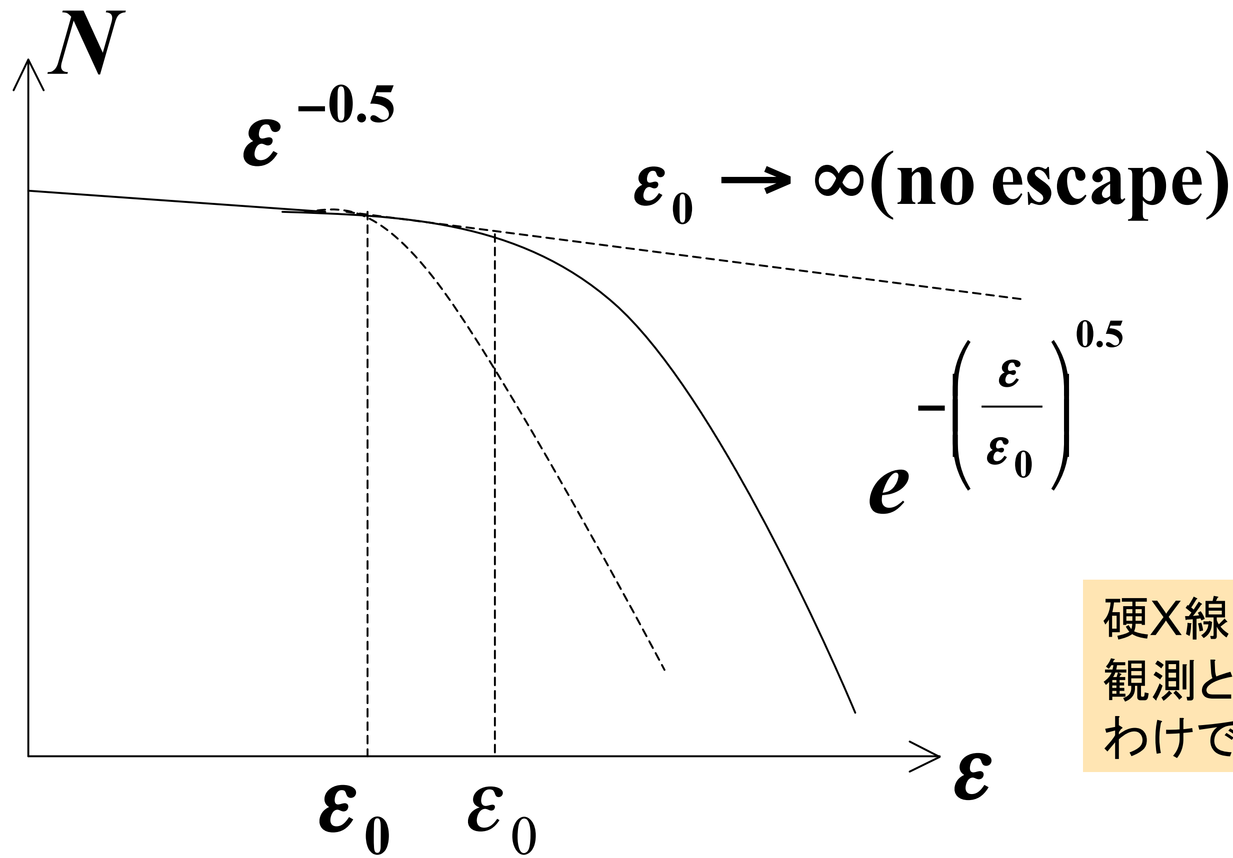
$$\frac{d}{d\varepsilon}\left(\frac{d\varepsilon}{dt}N\right) + \frac{N}{\tau} = 0$$

$$N \propto \varepsilon^{-0.5} \exp\left\{-\left(\frac{\varepsilon}{\varepsilon_0}\right)^{0.5}\right\} \qquad \varepsilon_0 = \frac{e^2E^2}{2m}\tau^2$$

τ時間走ってescapeするときのエネルギー

$$v = \frac{eE}{m}\tau \quad \rightarrow \quad \varepsilon = \frac{1}{2}mv^2 = \frac{1}{2}m\left(\frac{eE}{m}\right)^2\tau^2 = \frac{e^2E^2}{2m}\tau^2$$

電場加速のときの特徴的スペクトル

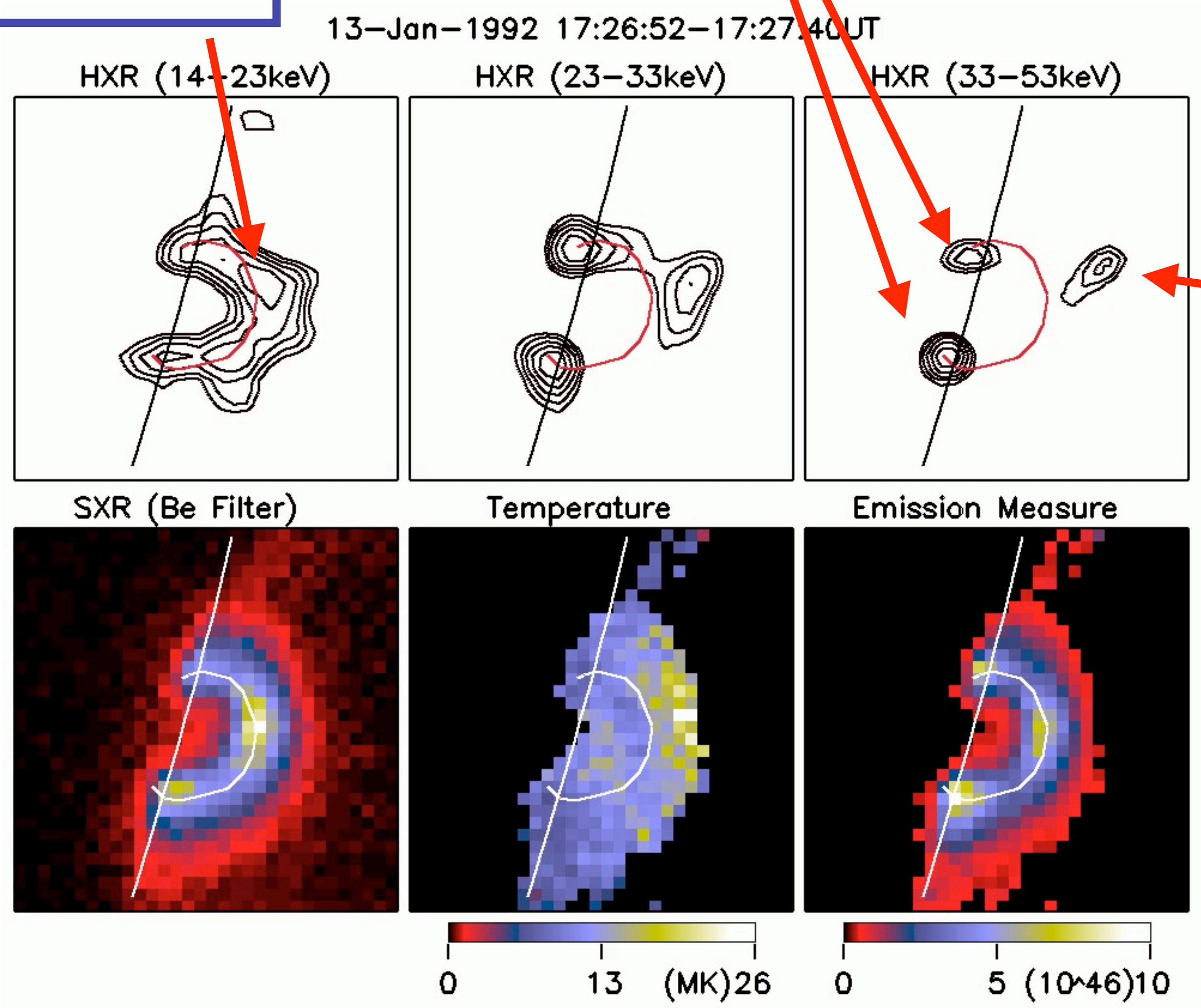


硬X線のスペクトル観測と整合しているわけではない

Three types of Hard X-ray Sources
Masuda et al.

(3) Looptop Gradual Source

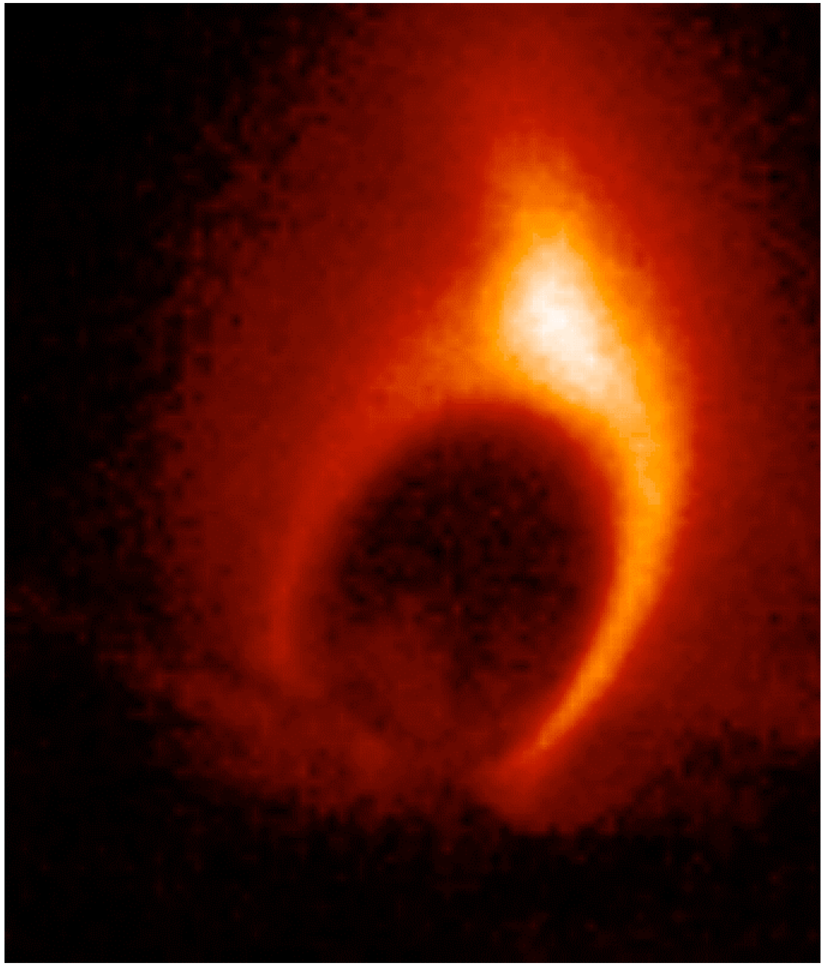
(1) Double Footpoint Sources

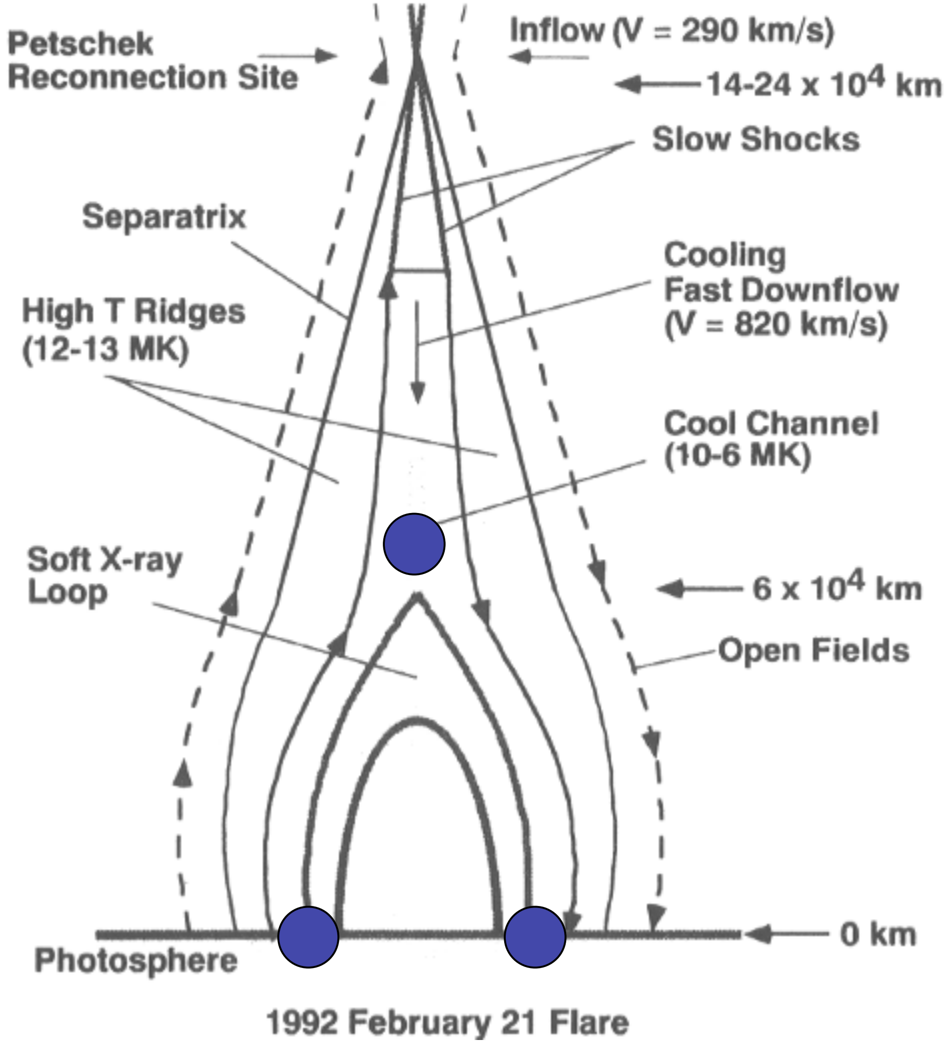


(2) Looptop Impulsive Source

Where does particle acceleration take place？

●＝hard X-ray source

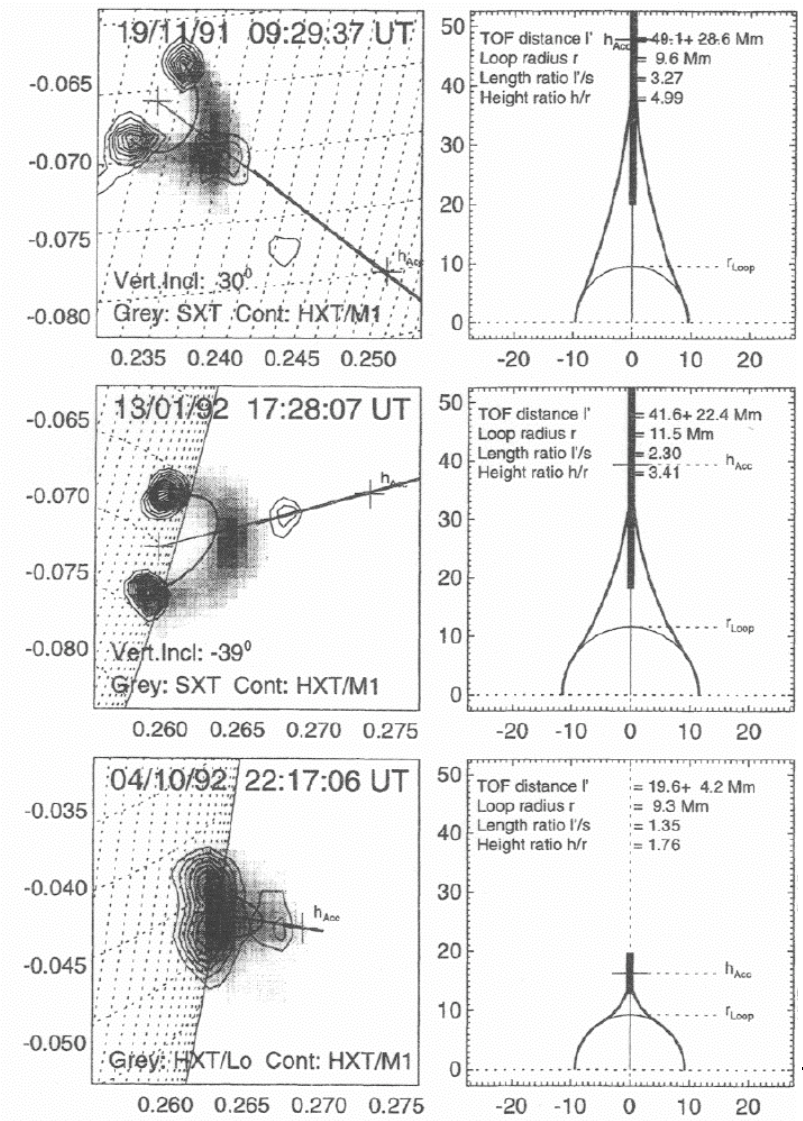




Tsuneta 1996

Location of acceleration site due to time-of-flight method

(CGRO/BATSE)

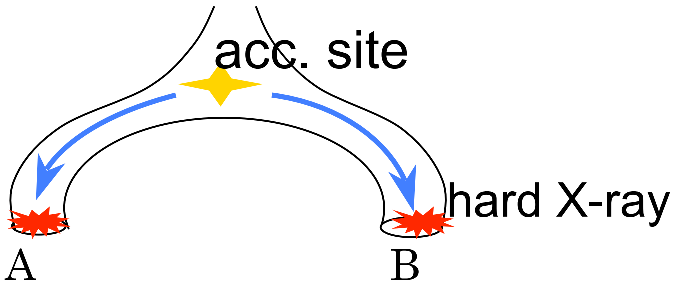


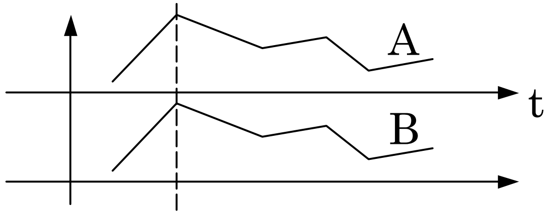
- Hard X-rays mainly come from footpoints
- Higher energy X-rays have earlier peak in time profile
- Time difference is due to difference in time-of-flight, giving distance between acceleration site and footpoint.
- Location of acceleration as obtained from time-of-flight method coincides in position with loop-top hard X-ray source or above.

Aschwanden *et al.* 1996

Where are electrons accelerated?

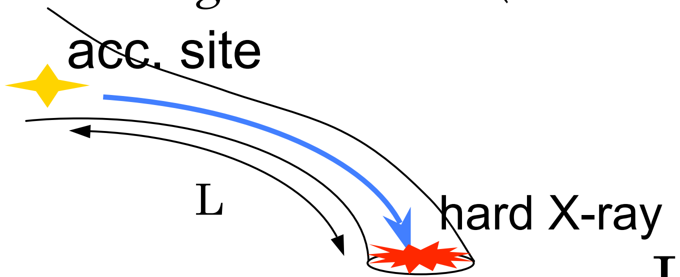
1. Simultaneous brightening of foot point (Sakao)

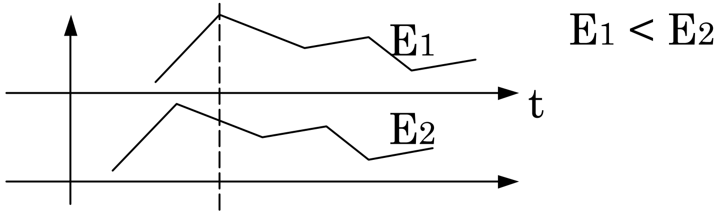




$\Delta t < 0.1$ sec. ⇒ loop top

2. Time of flight method (Aschwanden)





$L = \Delta t (v_2 - v_1)$ ⇒ loop top

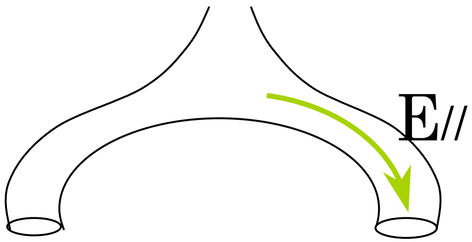
3. Yohkoh observation (Masuda, Kosugi)

loop top hard X-ray source

All point to localized acceleration site *near the loop top*.

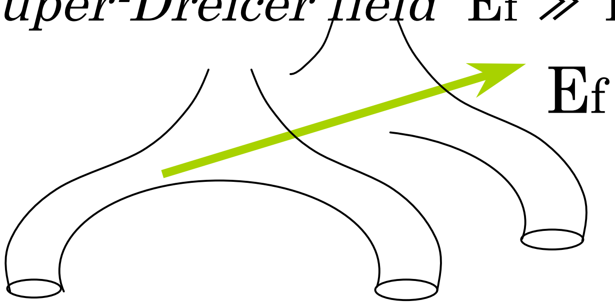
Acceleration mechanism

1. field aligned Sub-Dreicer field $E_{//} \ll E_D$



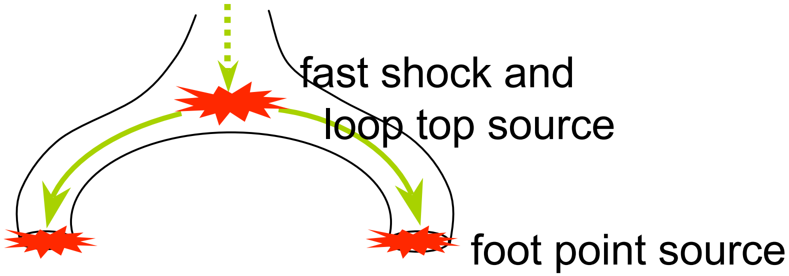
not consistent with
loop top acceleration site

2. Super-Dreicer field $E_f \gg E_D$ *at the neutral sheet*



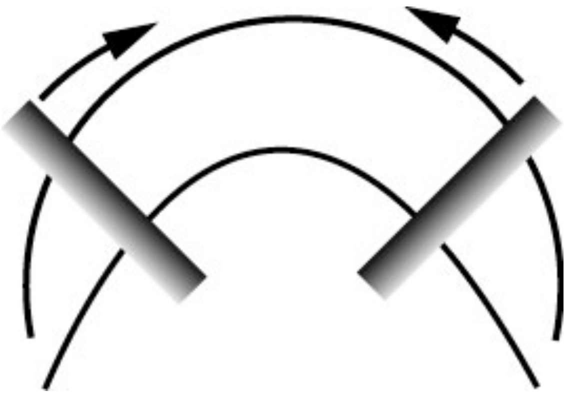
electron number problem

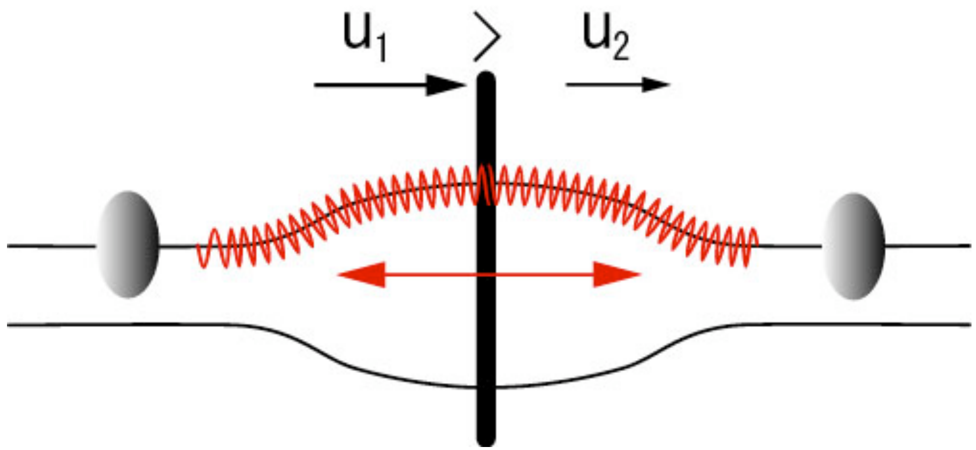
3. Shock Fermi acceleration

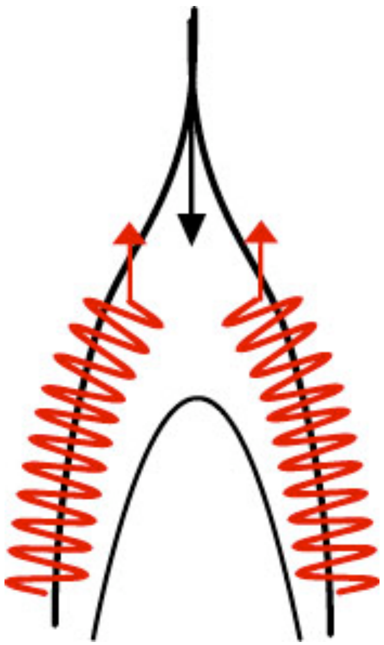


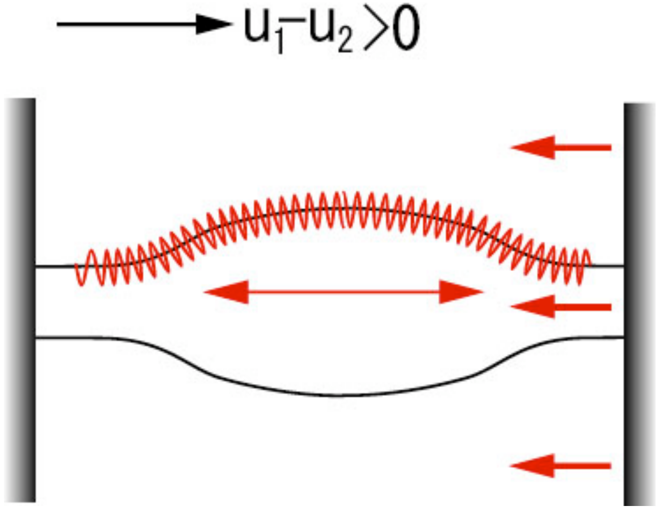
consistent with all observations

Fermi 加速



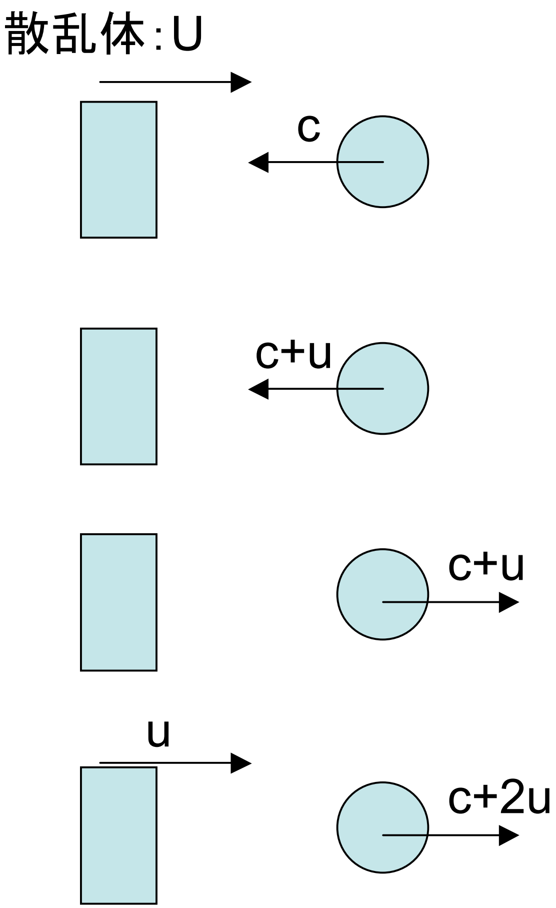






フェルミ加速の基礎

Fermi Ⅰ



$$\Delta\varepsilon = \frac{1}{2}m\left[(c+2u)^2 - c^2\right]$$

$$= \frac{1}{2}m4cu = 2mcu$$

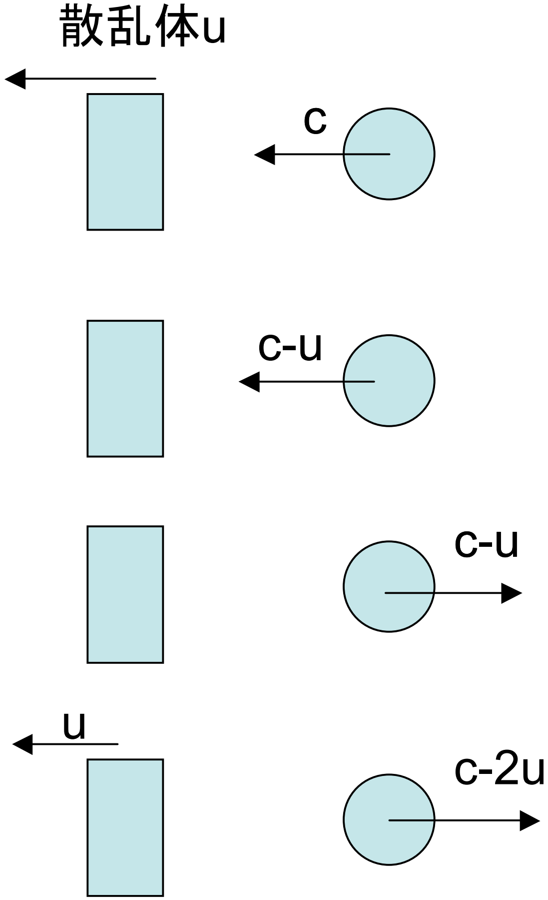
$$c >> u$$

$$\varepsilon = \frac{1}{2}mc^2$$

$$\frac{\Delta\varepsilon}{\varepsilon} = \frac{2cu}{\frac{1}{2}c^2} = 4\frac{u}{c}$$

$$p_+ \propto c+u$$

Fermi Ⅰ



$$\Delta\varepsilon = \frac{1}{2}m\left[(c-2u)^2 - c^2\right]$$
$$= -2mcu$$

$$c >> u$$

$$\frac{\Delta\varepsilon}{\varepsilon} = -4\frac{u}{c}$$

$$p_- \propto c + u$$

$$p_+ = \frac{c+u}{2c}$$

$$p_+ + p_- = 1$$

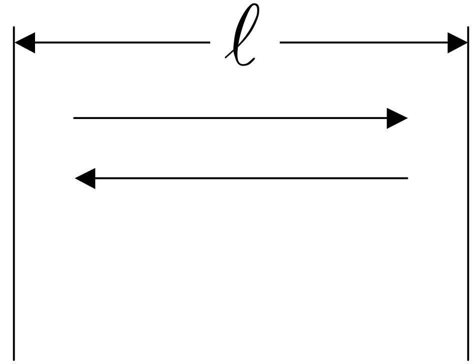
$$p_- = \frac{c-u}{2c}$$

Fermi Ⅰ

$$\Delta\varepsilon = \left(\frac{4u}{c}\right)\varepsilon \rightarrow \frac{d\varepsilon}{dt} = \frac{2u}{\ell}\varepsilon$$

1回の衝突で獲得するエネルギー

$$\rightarrow \varepsilon \propto \exp\left(\frac{2u}{\ell}t\right)$$



1秒間の衝突回数 $2\ell/c$

太陽

$$\frac{2u}{\ell} = \frac{2\times 500[\mathrm{km/s}]}{10^3[\mathrm{km}]} = 1[\mathrm{s}^{-1}]$$

$$t = 3[\mathrm{sec}] \rightarrow \varepsilon/\varepsilon_0 = 20 \qquad \varepsilon_0 = 0.2[\mathrm{kev}] \rightarrow \varepsilon = 4[\mathrm{kev}]$$

$$t = 5[\mathrm{sec}] \rightarrow \varepsilon/\varepsilon_0 = 150 \qquad \rightarrow \varepsilon = 30[\mathrm{kev}]$$

SNR

$$\begin{cases} \ell \sim 1pc \sim 3\times 10^{18}[\mathrm{cm}] \\ u \sim 5000[\mathrm{km/s}] = 5\times 10^{8}[\mathrm{cm/s}] \end{cases}$$

加速エネルギー $\varepsilon \propto \exp\left(\frac{2u}{\ell}t\right)$

加速時間

$$\tau \sim \frac{\ell}{2u} = \frac{3\times 10^{18}}{6.5\times 10^{8}} = 3\times 10^{9}[\mathrm{s}] = 100\mathrm{yr}$$

10^{14}[eV] (ASCA)

10^{15}[eV]?@= 2600年

10^{17}[eV] $t = 3000$年

10^{20}[eV] $t = 4400$年

陽子の衝突エネルギーロスとインジェクションエネルギー

$$-\left(\frac{d\mathring{a}}{dt}\right)_{loss} = 7.6\times 10^{-12}\, n\,[\mathrm{cm}^{-3}]\,E\,[\mathrm{MeV}]^{-\frac{1}{2}}\,[\mathrm{MeV/s}]$$

$$for \qquad E > E_c = \frac{1}{2} M v_{the}{}^2 \sim 0.5\,[\mathrm{MeV}] \quad (T = 2\times 10^6 [K])$$

Fermi Ｉを例にとる(陽子の場合）

$$\left.\frac{d\varepsilon}{dt}\right|_{加速} = \frac{u}{\ell} E$$

$$\left.\frac{dE}{dt}\right|_{加速} = \left|\frac{dE}{dt}_{\ loss}\right| \quad \text{at } E = E_c$$

$$n_{10} = 1, u = 1000[\mathrm{km/s}], \ell = 10^4[\mathrm{km}]$$

$$\rightarrow E_c = 0.11\left(\frac{n_{10}[cm^{-3}]\ell}{u}\right)^{\frac{2}{3}} [\mathrm{MeV}] \qquad \rightarrow E_c = 0.5[\mathrm{MeV}]$$

陽子加速には別の加速機構が必要？

電子の衝突エネルギーロスとインジェクションエネルギー

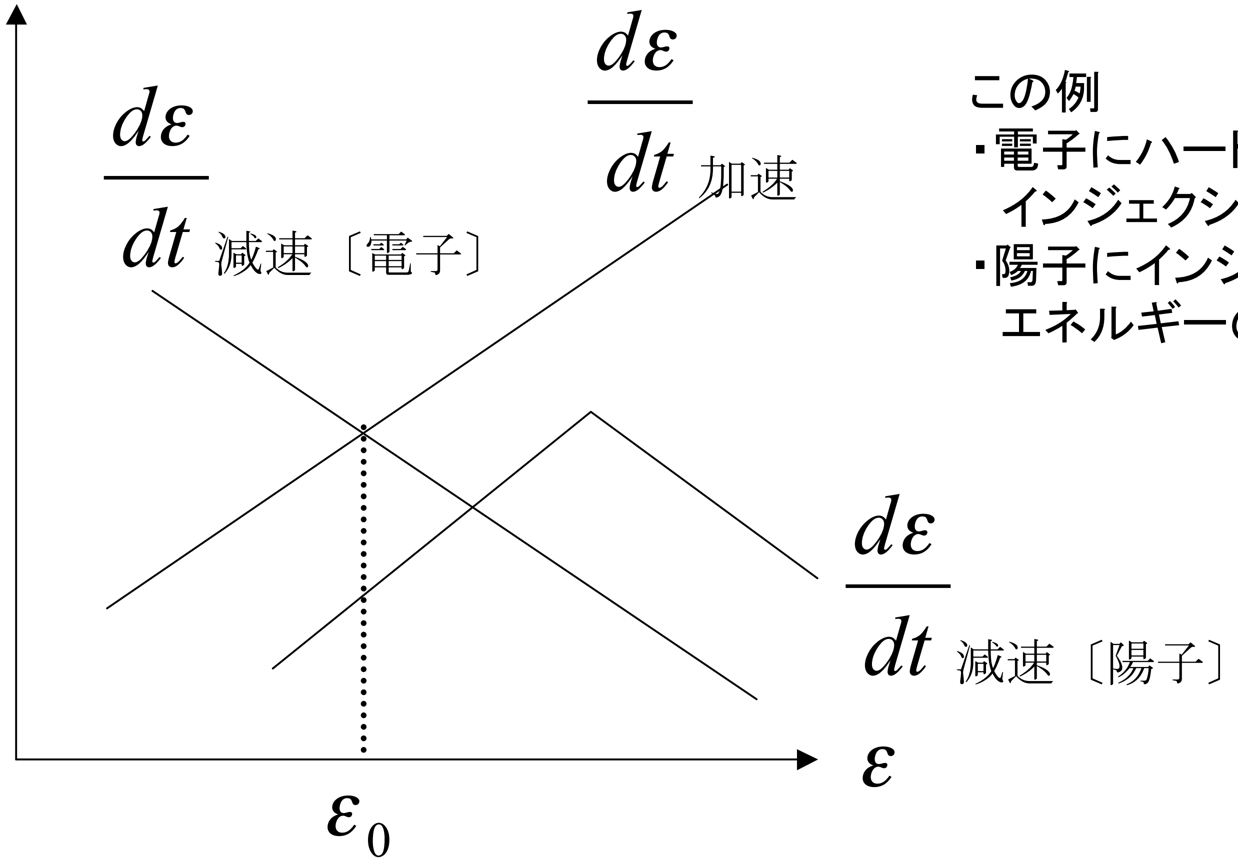
$$-\left.\frac{d\varepsilon}{dt}\right|_{loss} = 3.0\times10^{-10}\,n[\mathrm{cm}^{-3}]\frac{1}{\beta}[\mathrm{keV/s}],\ \beta \equiv \frac{\upsilon}{c}$$

Fermi Ｉを例にとる(電子の場合）

$$\begin{cases} n = 3\times10^{10}[cm^{-3}] & \beta_c = 0.32 \\ & E_c = 26[\mathrm{keV}] \\ n = 3\times10^{11}[cm^{-3}] & E_c = 160[\mathrm{keV}] \end{cases}$$

電子加速には別の加速機構が必須！

電子と陽子の インジェクションエネルギー

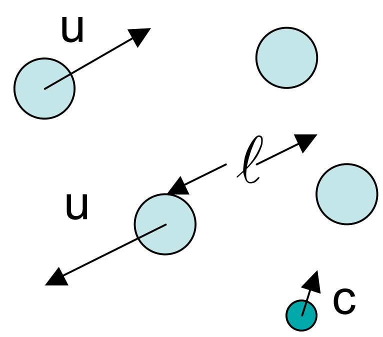


この例
- 電子にハードルの高い インジェクションエネルギー
- 陽子にインジェクション エネルギーのない場合

Fermi Ⅱ (stochastic)

$$\Delta\varepsilon = \left[\frac{c+u}{2c}\frac{4u}{c} + \frac{c-u}{2c}\left(-\frac{4u}{c}\right)\right]\varepsilon$$

$$= 4\left(\frac{u}{c}\right)^2 \varepsilon$$



$$\frac{d\varepsilon}{dt} = 4\left(\frac{u}{c}\right)^2 \varepsilon \frac{c}{\ell} = \alpha$$

平均衝突時間 $T = \frac{\ell}{c}$

Relativistic
の場合を例題
として

$$c \sim const \rightarrow \varepsilon = \varepsilon_0 e^{\alpha t}$$

スペクトル $\frac{d}{d\varepsilon}\left(\frac{d\varepsilon}{dt}N\right) + \frac{N}{t} = 0$

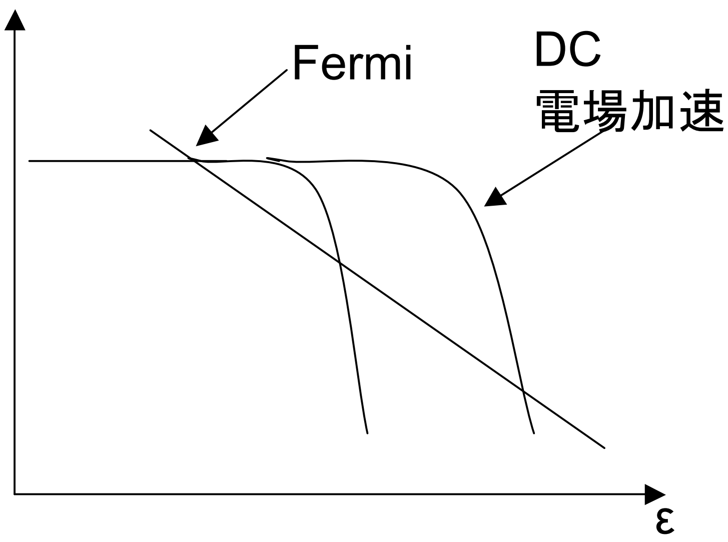
$$\frac{d\varepsilon}{dt} = \begin{cases} \alpha\varepsilon \begin{cases} \alpha = \frac{2u}{\ell} & \text{(Fermi I)} \\ \alpha = \frac{4u^2}{c\ell} & \text{(Fermi II} - \textit{relativistic}\text{)} \end{cases} \\ \delta\varepsilon^{\frac{1}{2}} (\textit{Fermi II non} - \textit{relativistic}) \quad \delta = \frac{2\sqrt{2}u^2 m^{\frac{1}{2}}}{\ell} \end{cases}$$

Fermi Ⅱ

$$N \propto \varepsilon^{-\left(1+\frac{1}{\alpha\tau}\right)} \rightarrow \varepsilon^{-1} (\tau \rightarrow \infty : \text{no escape})$$

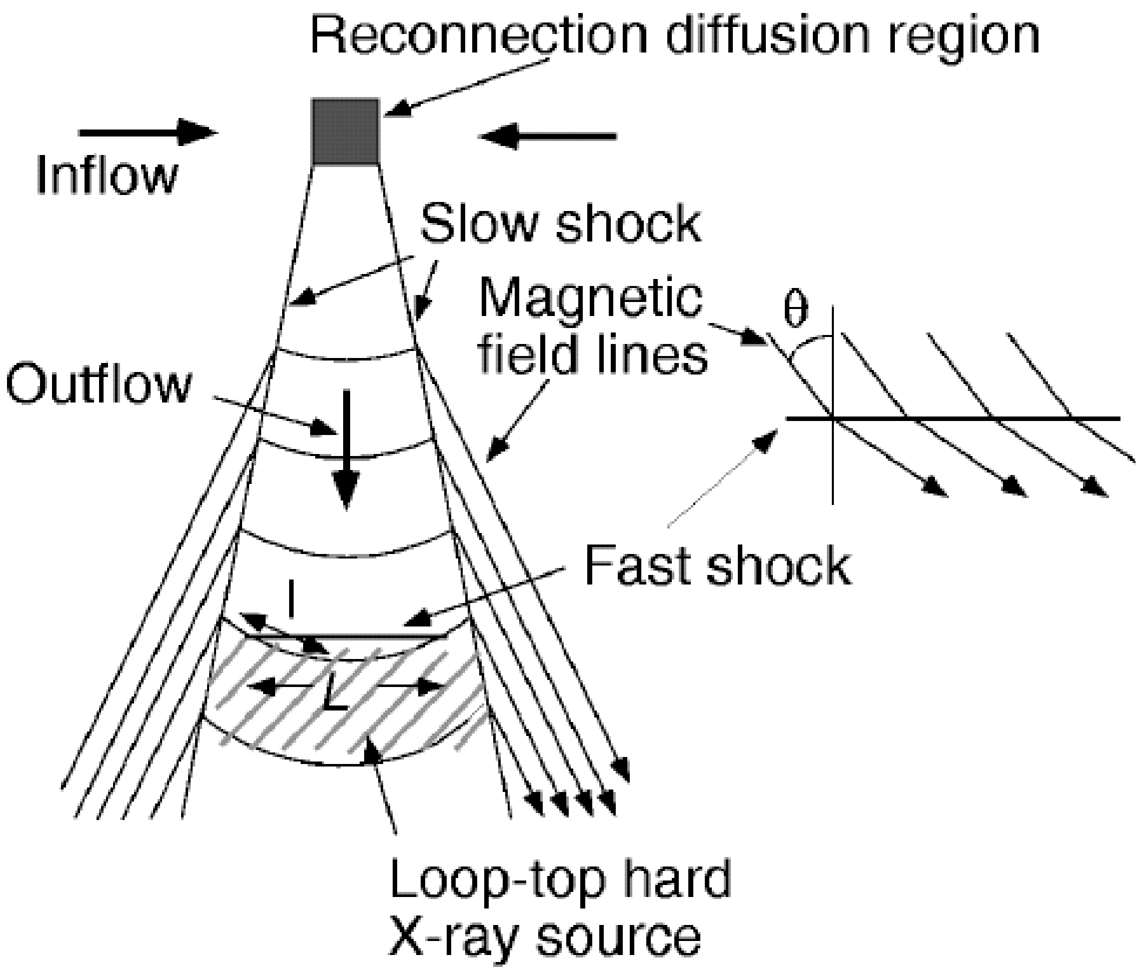
太陽

$$1+\frac{1}{\alpha\tau} = 3 \sim 4 \rightarrow \alpha\tau \sim \frac{1}{3},\ \tau \approx 10\,\text{sec}$$



	スペクトル	加速 Time scale	Injection Energy
$DC-\vec{E}$	$\varepsilon^{-0.5}\varepsilon^{-\left(\frac{\varepsilon}{\varepsilon_0}\right)^{\frac{1}{2}}}$ $\varepsilon_0=\frac{e^2E^2}{2m}\tau^2$	$\varepsilon \propto t^2$	$E \sim E_D$
Betatron	$\varepsilon^{-\left(1+\frac{1}{dt}\right)}$ $\alpha=\frac{1}{B}\frac{dB}{dt}$	$\varepsilon \propto \exp(\acute{a}t)$	あり
Fermi Ⅰ	$\varepsilon^{-\left(1+\frac{1}{dt}\right)}$ $\alpha=\frac{2u}{\ell}$	$\varepsilon \propto \exp(\acute{a}t)$	$p:E_c=0.5[\mathrm{MeV}]$ $e:E_c=20\sim100[\mathrm{keV}]$ あり
Fermi Ⅱ (rel)	$\varepsilon^{-\left(1+\frac{1}{dt}\right)}$ $\alpha=\frac{4u^2}{c\ell}$	$\varepsilon \propto \exp(\acute{a}t)$	あり
Fermi Ⅱ (non-rel)	$\varepsilon^{-0.5}\varepsilon^{-\left(\frac{\varepsilon}{\varepsilon_0}\right)^{\frac{1}{2}}}$ $\varepsilon_0=4\tau^2mu^4/\ell^2$	$\varepsilon \propto t^2$	あり

リコネクションのアウトフロー領域は理想的な粒子加速場所？

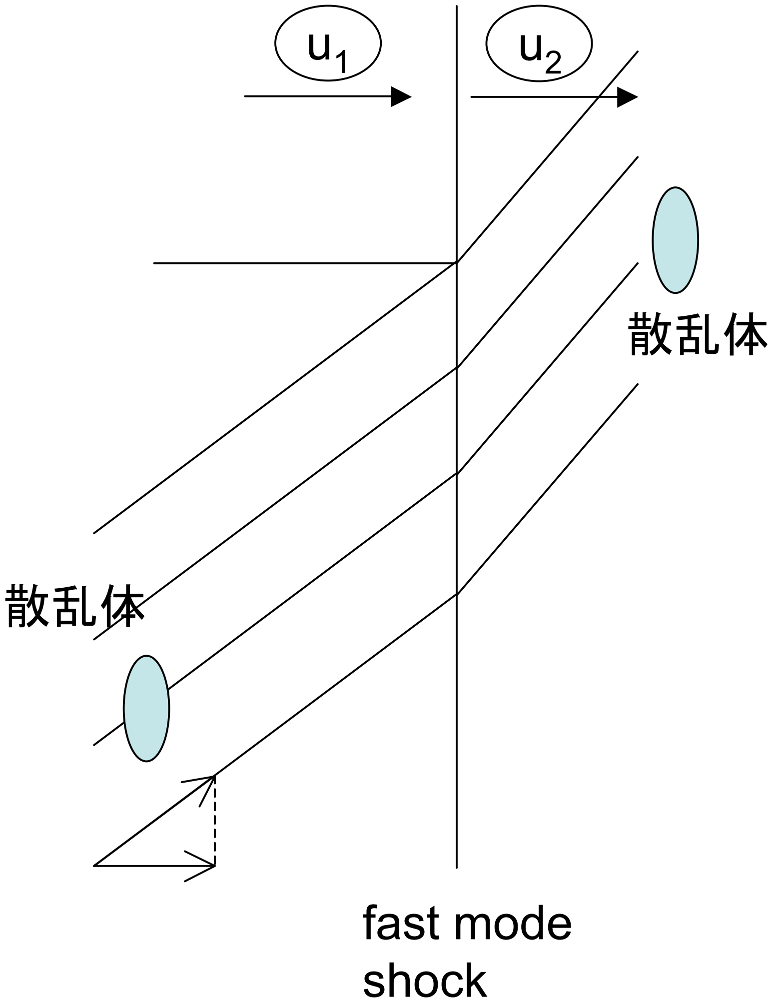


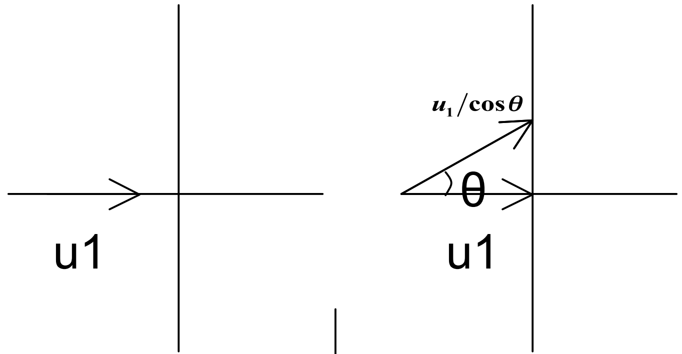
Diffusive shock acceleration with oblique (perpendicular) shock
(Tsuneta & Naito, ApJ, 495, L67, 1998)

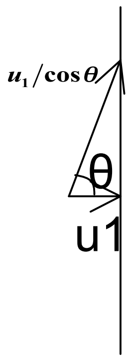
✓Two Slow shocks serve to contain accelerated electrons with mirror configuration.

✓Injection problem associated with Fermi acceleration can be overcome with pre-heating with slow mode shocks to 20MK, and efficient acceleration with oblique shocks.

斜め衝撃波による粒子加速







斜め衝撃波により
散乱体の早さが早く
なる

$$\Delta\varepsilon = \left(\frac{4u}{c}\right)\varepsilon \rightarrow \frac{d\varepsilon}{dt} = \frac{2u}{\ell}\varepsilon$$

$$\Delta\varepsilon = \left(\frac{4u}{c\cos\theta}\right)\varepsilon \rightarrow \frac{d\varepsilon}{dt} = \frac{2u}{\ell\cos\theta}\varepsilon$$

加速効率の増大ー＞
インジェクションエネルギーの低減に寄与

第2のインジェクション問題

粒子を拡散させる(跳ね返す)適切な波があるか？
Alfven wave?
whistler wave?

$$l = \frac{k_1}{u_1} + \frac{k_2}{u_2}$$

l diffusion length

k diffusion coefficient

u flow speed

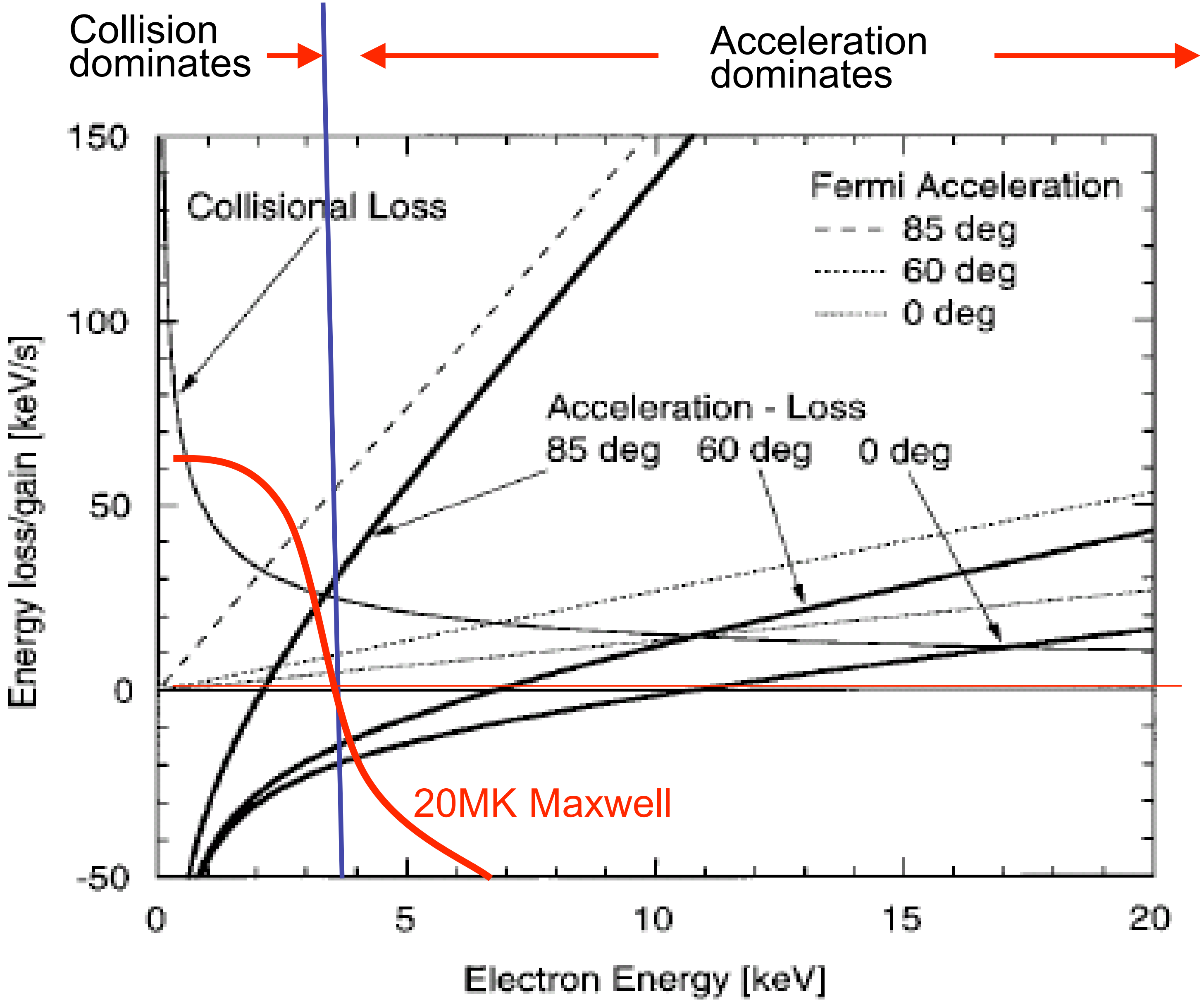
$$l > l_{Bohm} = \eta\kappa_B / u \approx 2\eta E/(3m\omega_{ce}u) \approx 0.06\eta \text{ km for } E = 100\text{keV}, B = 10\text{G}$$

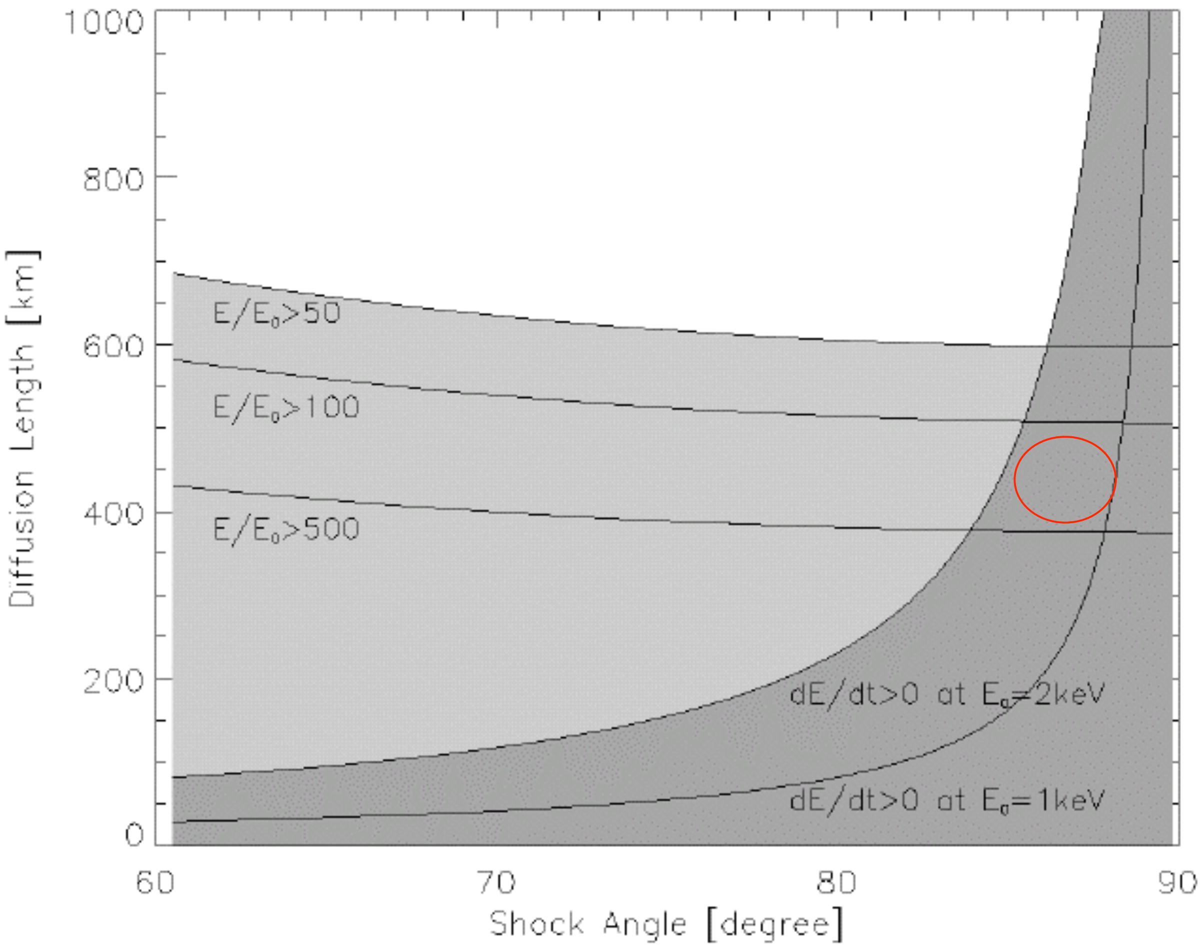
κ_B Bohm diffusion coefficient

$\eta = 1\text{-}100$

If we conservatively assume $\eta = 10^4$, $l = 600$ km

Fermi加速のInjection問題



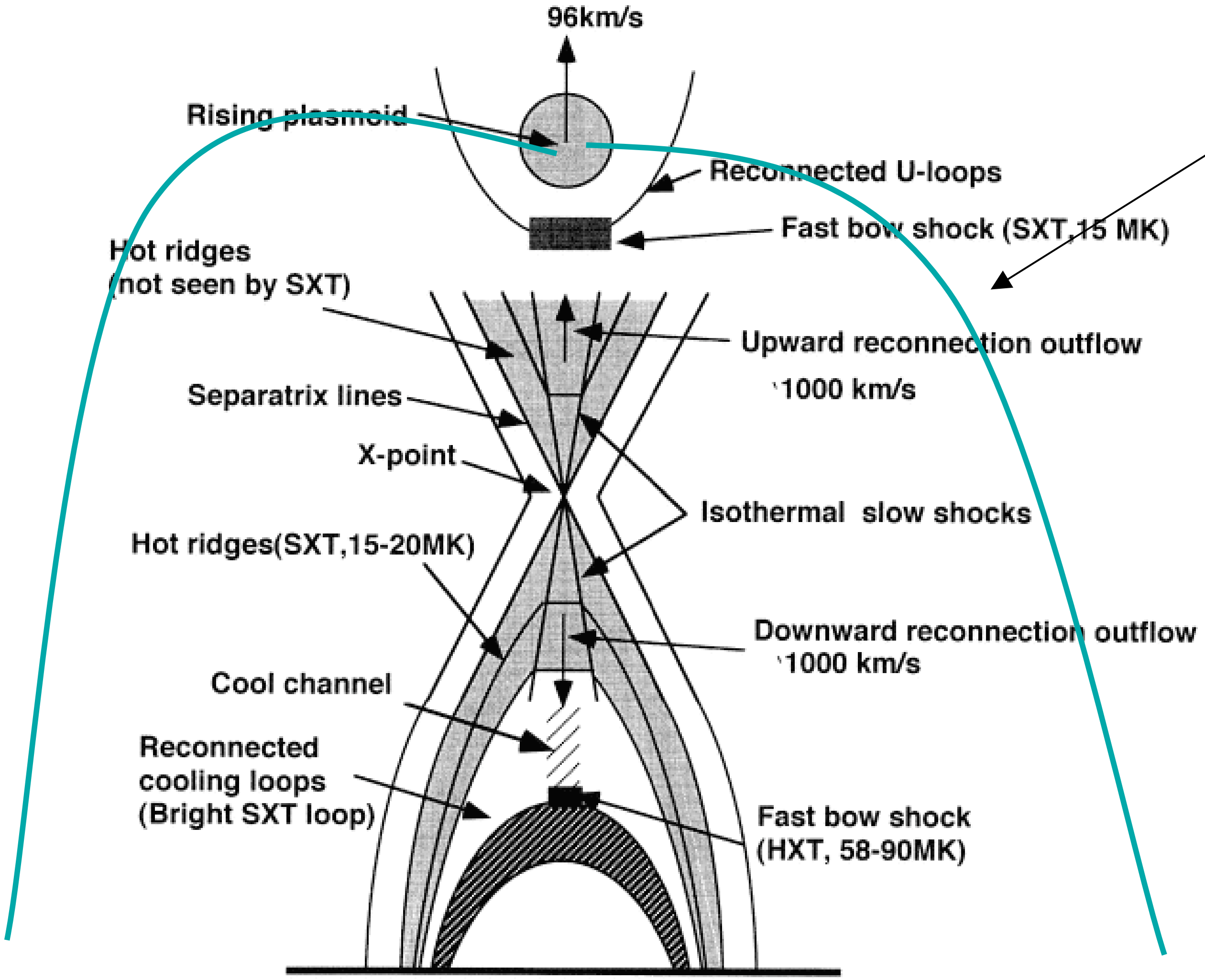


10MeVまで
電子加速可能

Tsuneta&Naito 1998

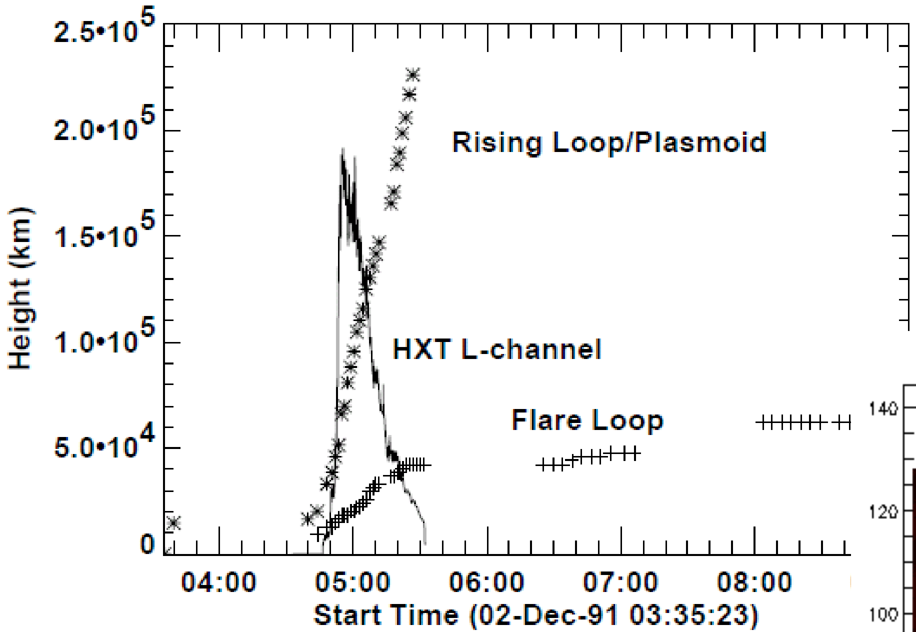

(2)
04:52:49-04:54:59
(3)
04:54:59-04:56:53
(4)
04:56:53-04:59:01
(6)
05:01:03-05:03:11
(7)
05:03:11-05:05:11
(8)
05:05:11-05:07:37
(10)
05:09:39-05:15:05
(11)
05:15:05-05:17:43
(12)
05:17:43-05:19:43
(4)
(8)
(12)

Upward motion of plasmoid



Many flares emit plasmoid before the onset of flares

Plasmoid emission coincides in time with HXR peak
Electron acceleration～dynamical phenomena

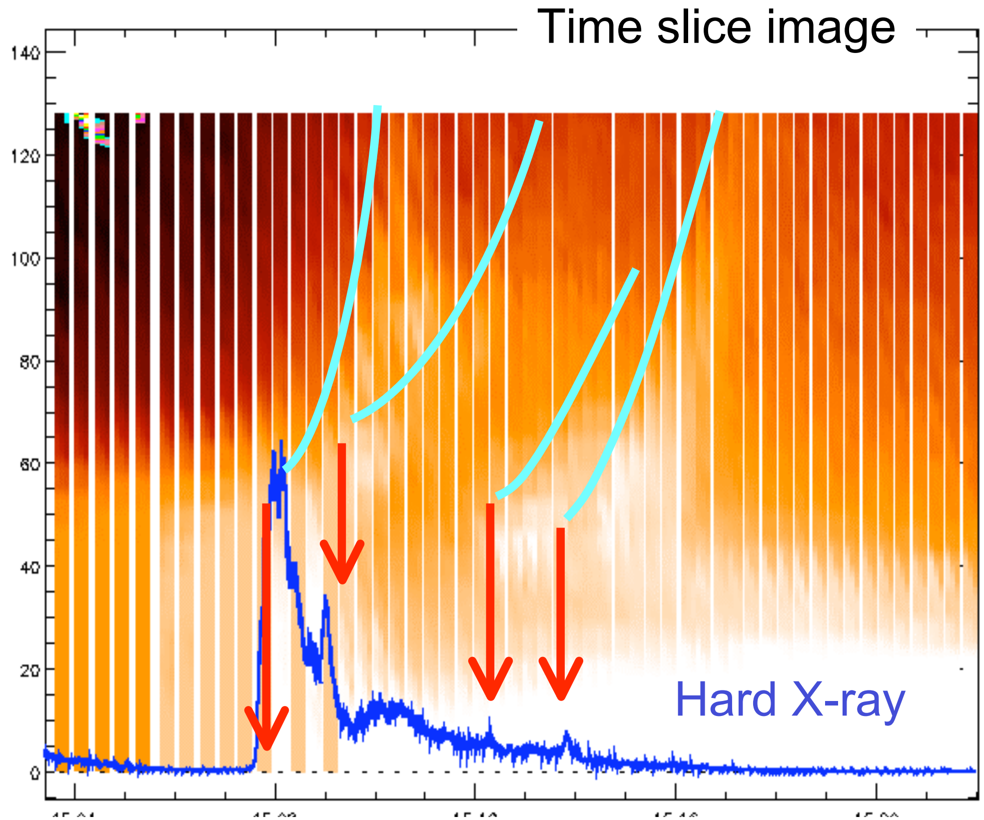


Tsuneta, ApJ, (1998)

Hard X-rays in association
With plasmoid

- Individual plasmoid coincides in time with hard X-ray peak.

プラズモイドの時間一高度図



Takasaki et al. (2005)

Summary

- We have some understanding on the heating process, while particle acceleration is poorly understood.
- Observations indicate that acceleration site is located close to the reconnection site.
- Acceleration mechanism indicates shock-related acceleration mechanism such as Fermi acceleration, some form of turbulent (wave) acceleration.
- Both electrons and ions are accelerated via the same mechanism.
- Dynamical phenomena driven by MHD instability resulting in plasmoid eruption may be related to particle acceleration.
- There are flares with intense heating without acceleration.