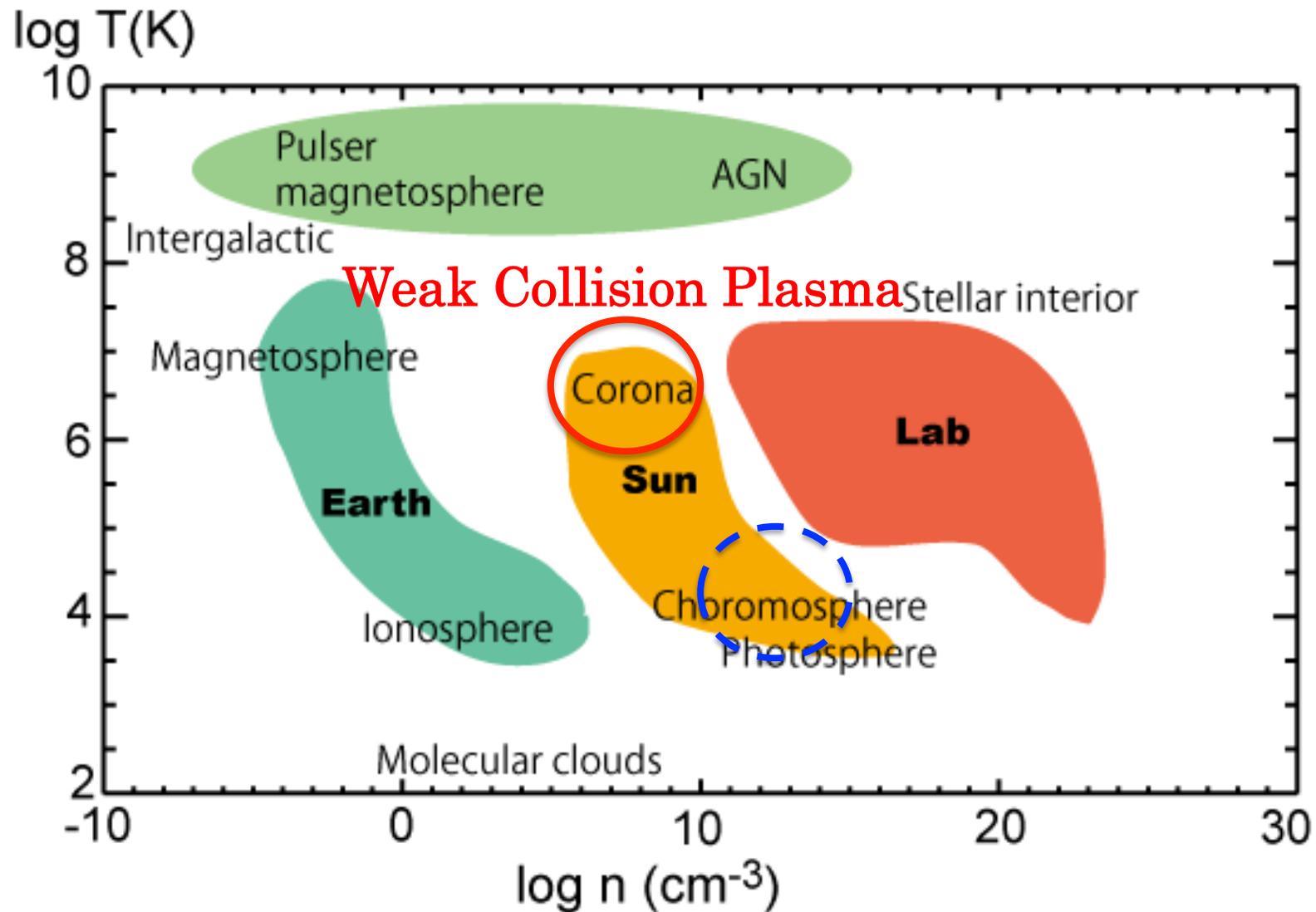




Solar-Cで探る 磁気リコネクションの物理

Shinisuke Imada (Nagoya Univ., STEL)

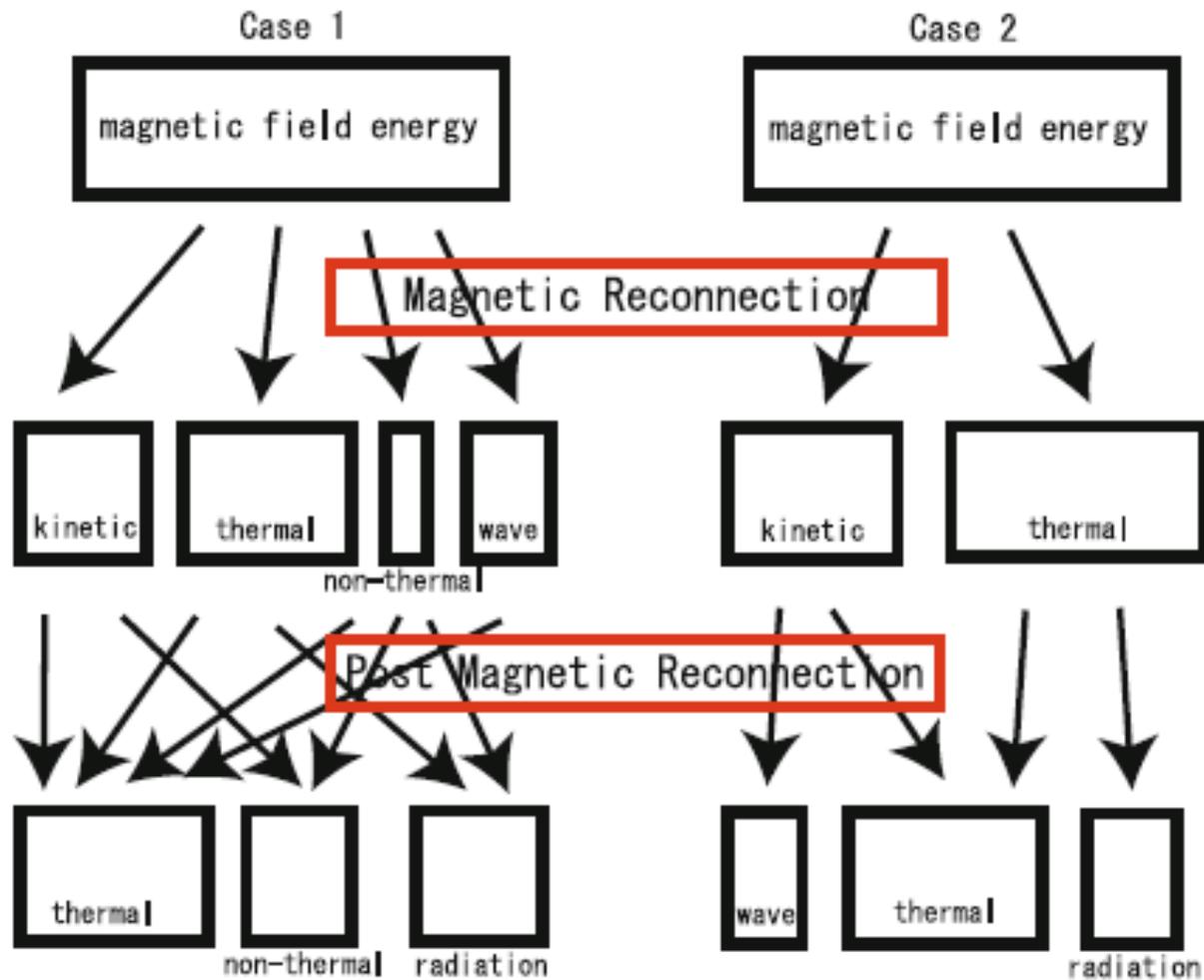
Plasmas conditions in solar corona



Difference from collisionless plasma

- Momentum transfer by coulomb collision
衝突による運動量交換
- Thermal conduction along magnetic field
衝突による熱伝導
- Ionization and recombination
衝突による電離・再結合
- Radiative energy loss (not synchrotron radiation)
衝突による輻射

What plasma parameter control the energy conversion rate?



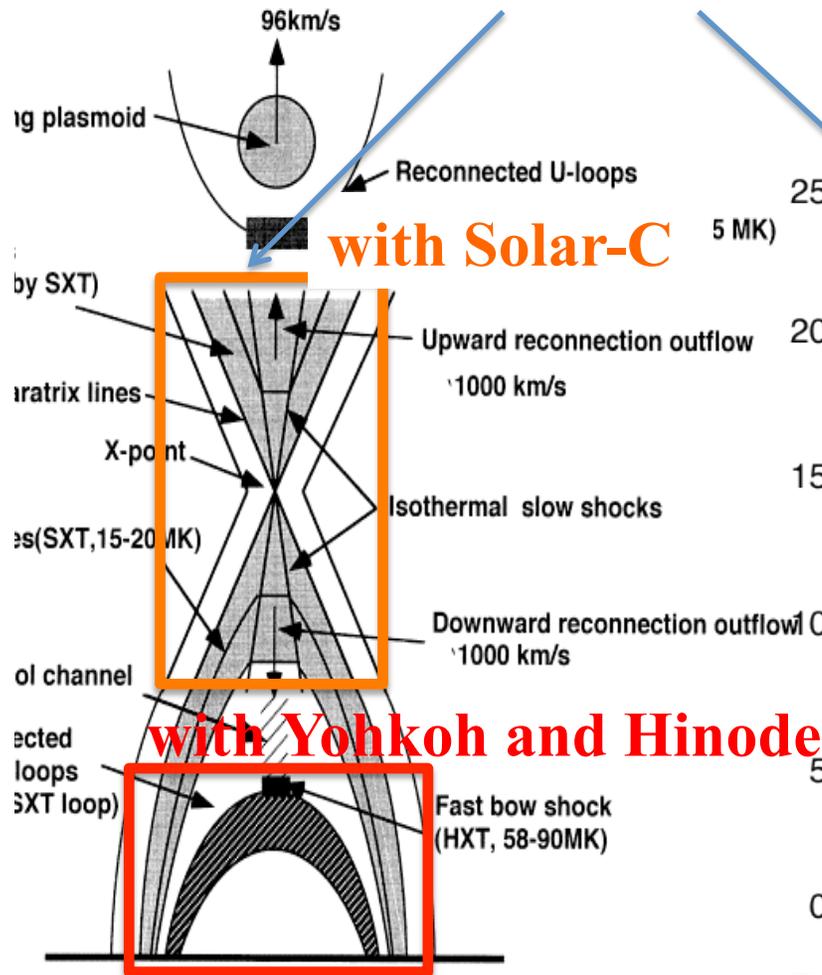
What controls the energy conversion rates?

Target of MRX obs.

- Heating associated with/without slow-shock.
 - Electron heating
 - Ion heating (Possible???)
- Alfvénic flow
 - Doppler shift measurement
 - Ionization information
- Particle acceleration
 - Supra-thermal & High energy electron acc.

Standard model for Solar Flare

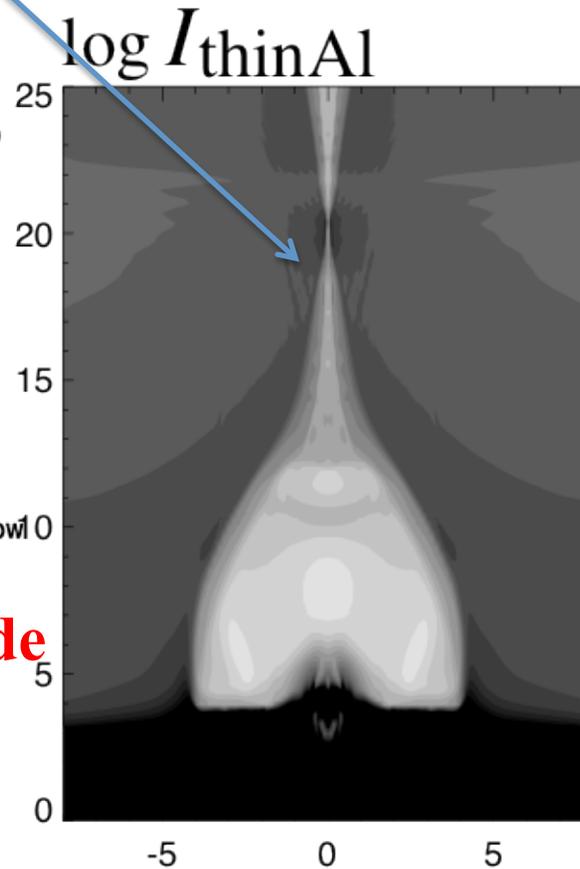
Hot & Fast Flow should be observed!



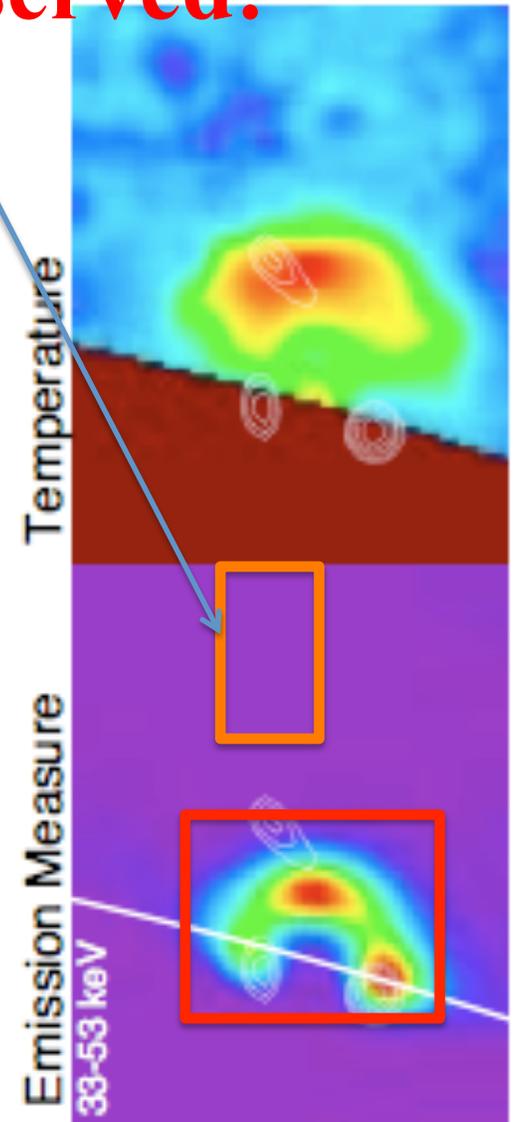
Tsuneta et al., 1996

with Solar-C

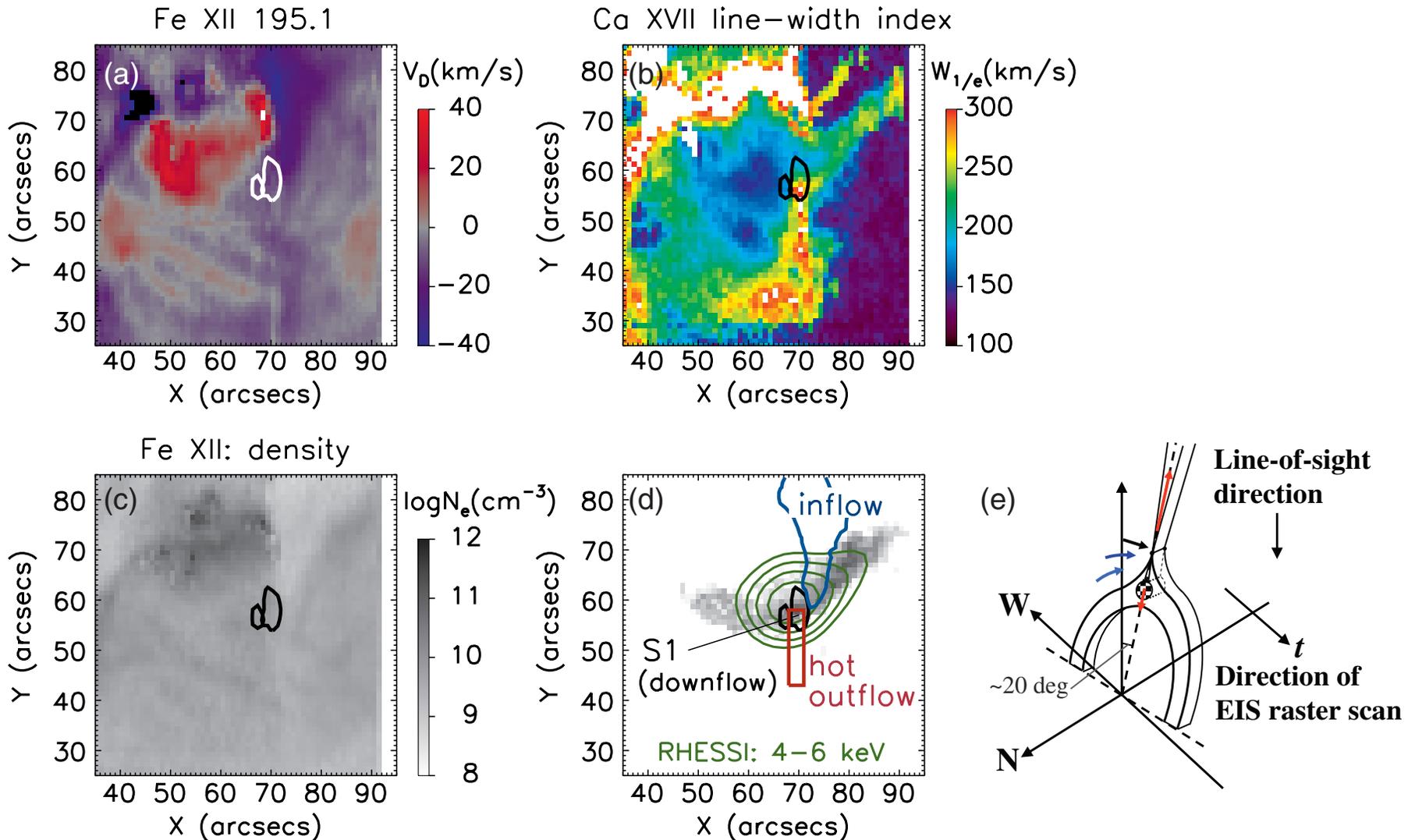
with Yohkoh and Hinode



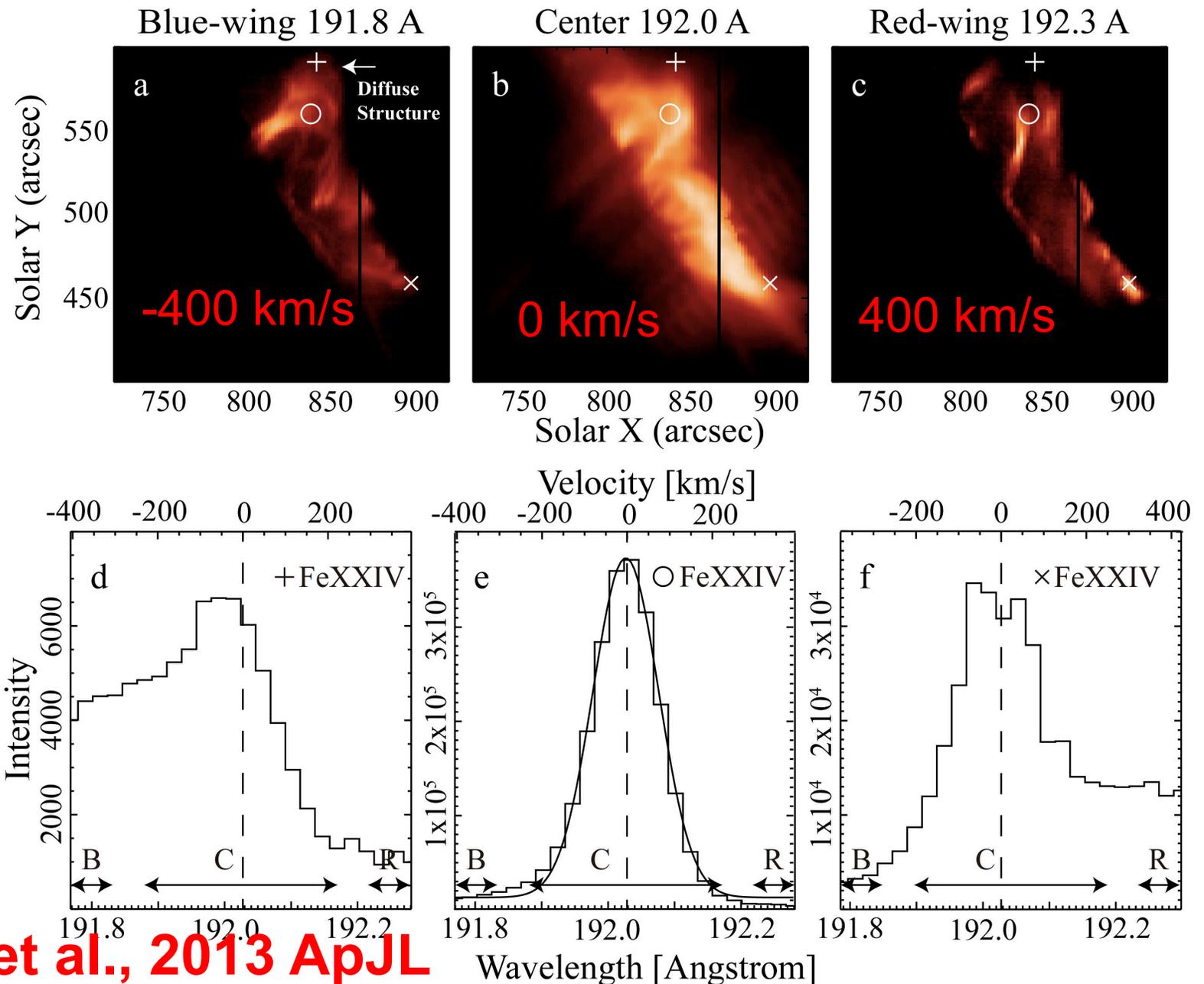
Yokoyama & Shibata 2001



Hara et al. 2011 ApJ RX flows



Spectroscopic obs: EIS Line Profiles

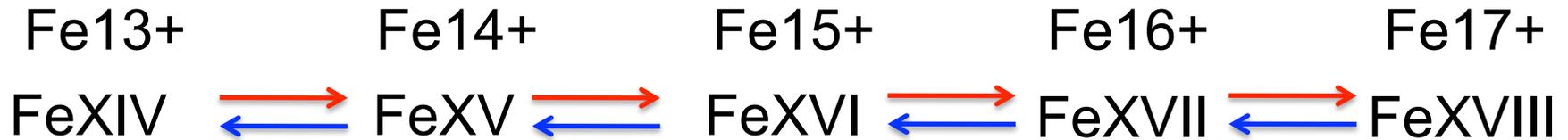


Thermal Non-Equilibrium Plasma

Because RX is highly dynamic, plasma may not reached to Equilibrium stage! This is new regime for Solar physics obs.

- **Non-Gaussian Distribution function** ガウス分布でない
 - Power-law distribution, beam plasma
 - time scale for equilibrium is very short
(kinetic regime or e-e or i-i collision)
- **Different temperature in different species**
 - $T_i > T_e$
 - time scale for equilibrium is relatively long
(e-i collision) プラズマ種で平衡でない
- **Ionization non-equilibrium**
 - strong heating or flare
 - time scale for equilibrium is long 電離非平衡

Ionization Process



→ ionization ← recombination

$$\frac{\partial n_i^Z}{\partial t} + \nabla \cdot n_i^Z \mathbf{v} = R_i^Z$$

$$(Z = 1, \dots, N_{\text{elem}}) \quad (i = 1, \dots, N_{\text{ion}}^Z),$$

where

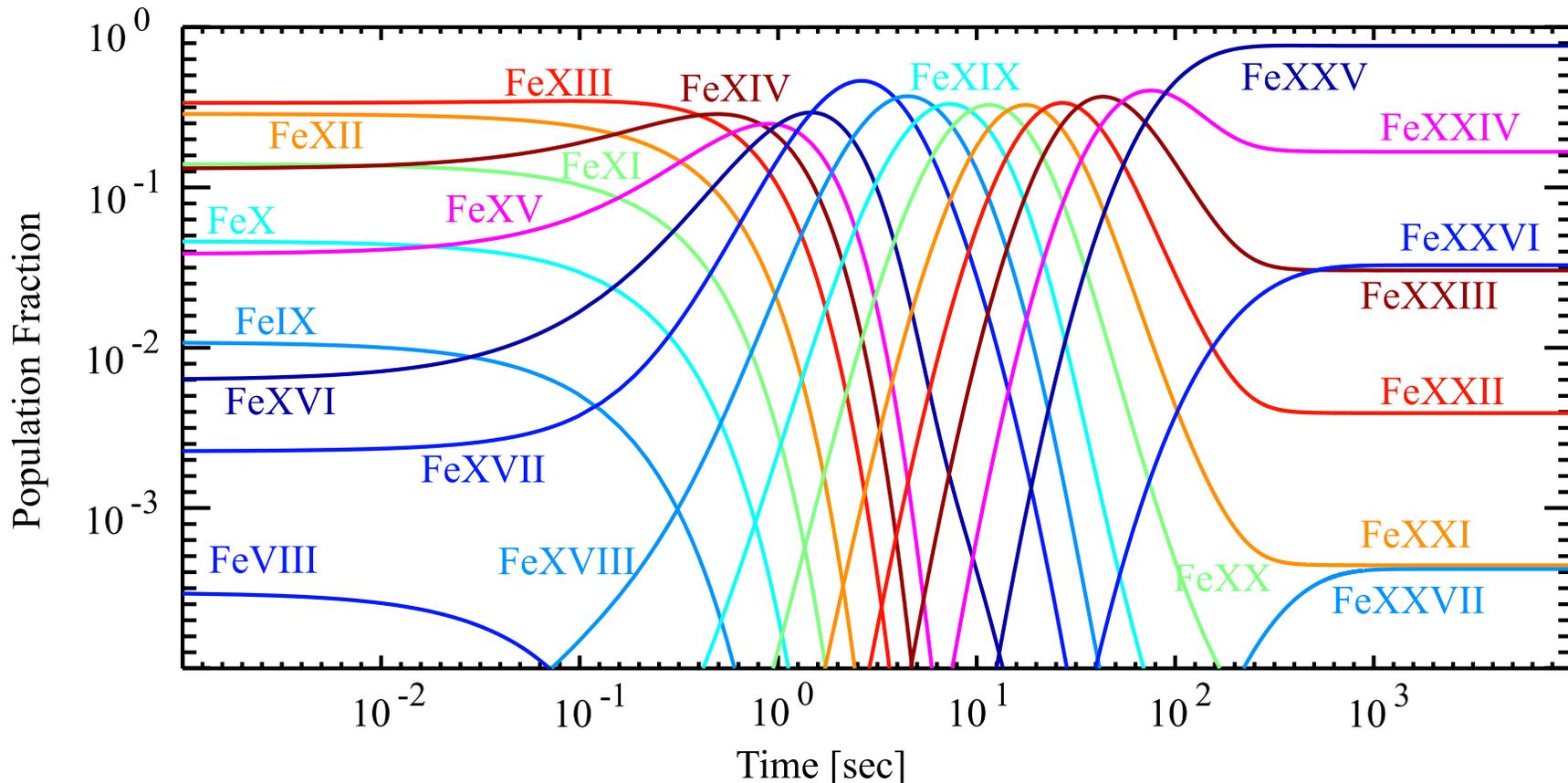
$$R_i^Z = n_e \left[n_{i+1}^Z \alpha_{i+1}^Z + n_{i-1}^Z S_{i-1}^Z - n_i^Z \left(\alpha_i^Z + S_i^Z \right) \right],$$

α collisional and dielectronic recombination

S collisional ionization

We can discuss the history of heating!

Example of Ionization Calculation



Initial : Ionization Equilibrium

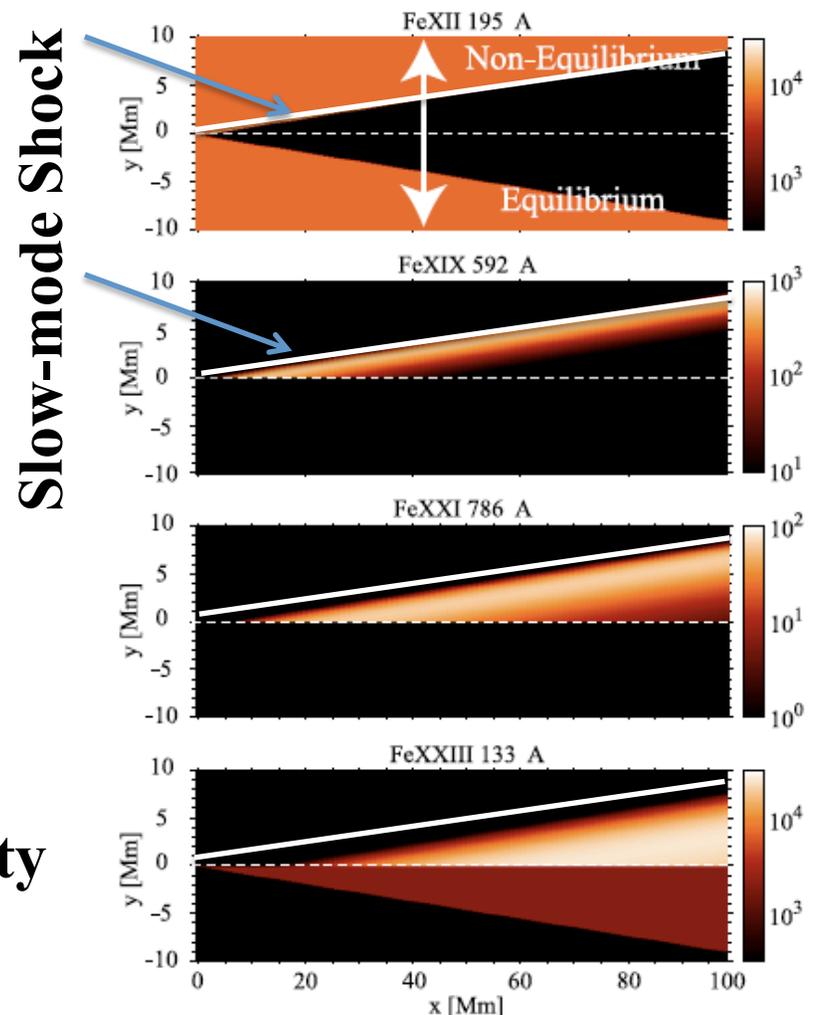
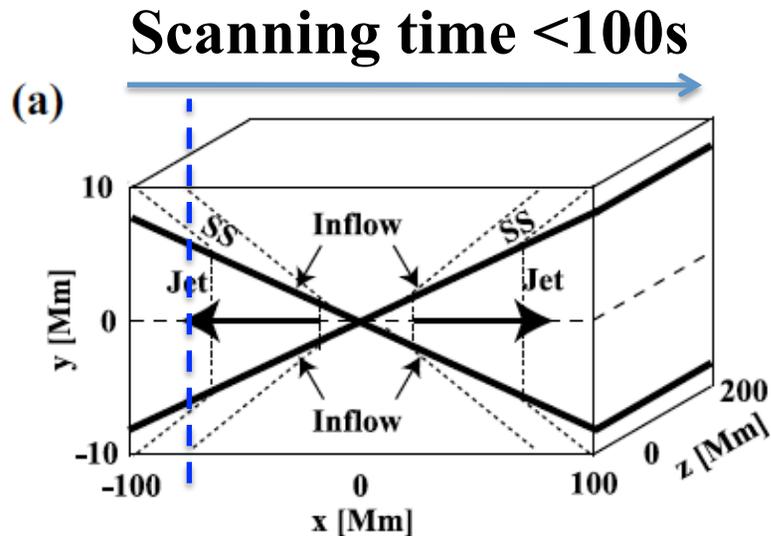
Te: 1.5 MK → 31.3 MK @ t=0

Ne: 2.45 x 10⁹ /cc

How to diagnose MRX region?

Ionization process with line spectroscopy

Spatial resolution is enough to resolve.

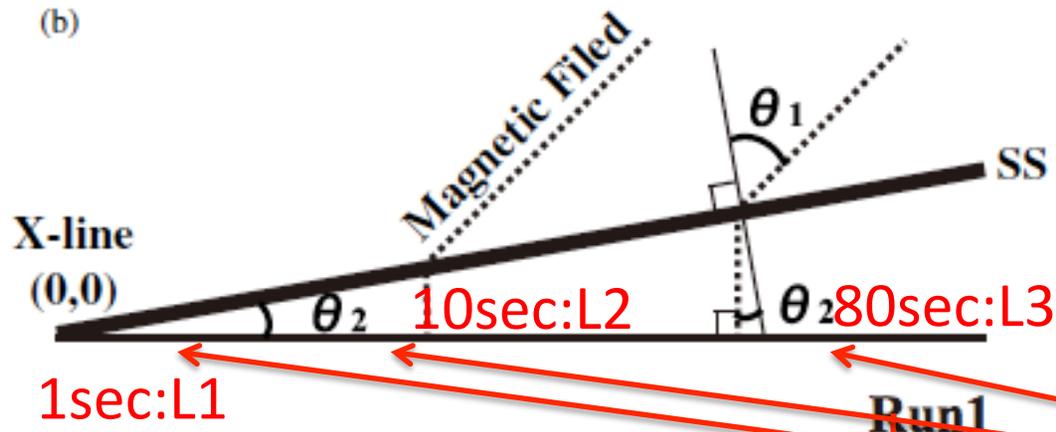


Fast scanning ($< \text{Alfvén time} \sim 100\text{s}$)
with high throughput spectrometer.
Wide temperature coverage.

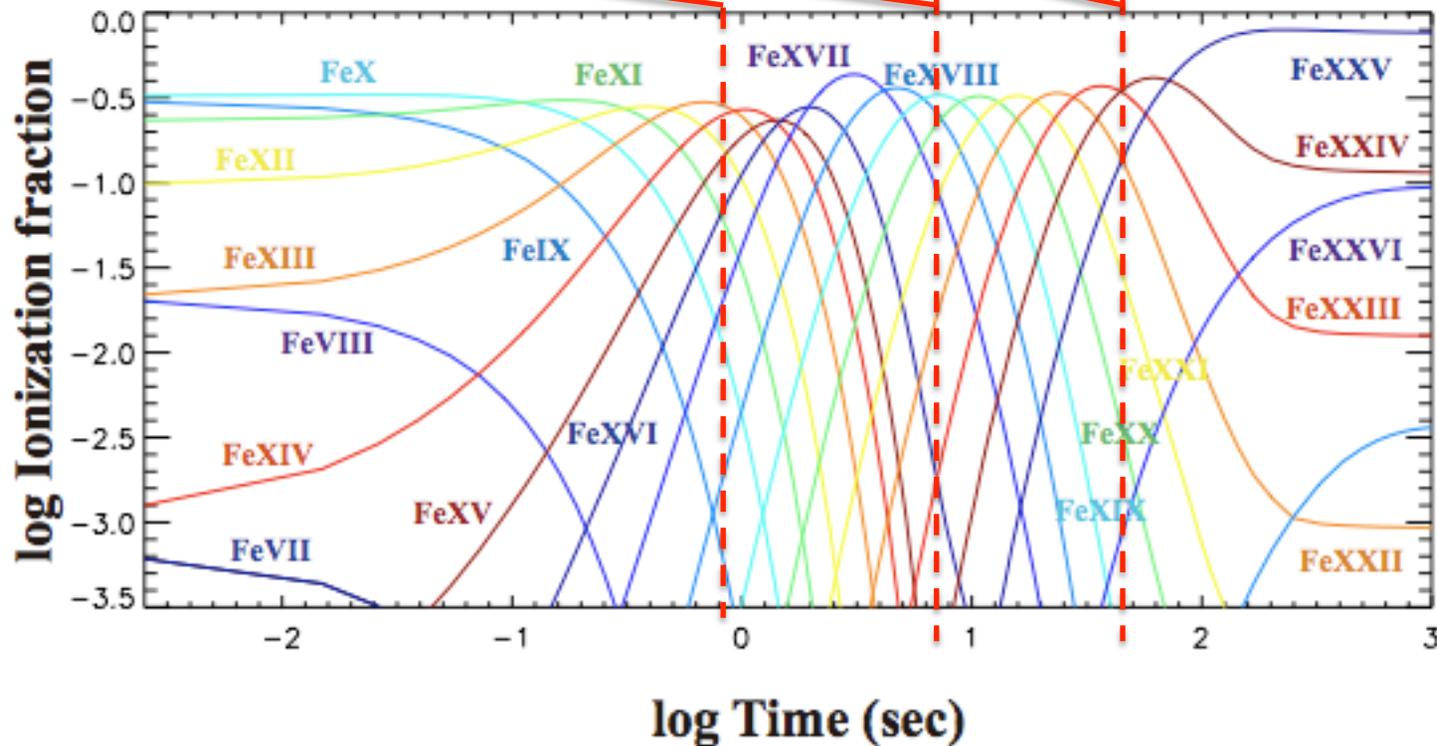
Diagnose velocity, temperature, density
with spectroscopic observation!

Imada et al., 2011 ApJ

How to diagnose MRX region?

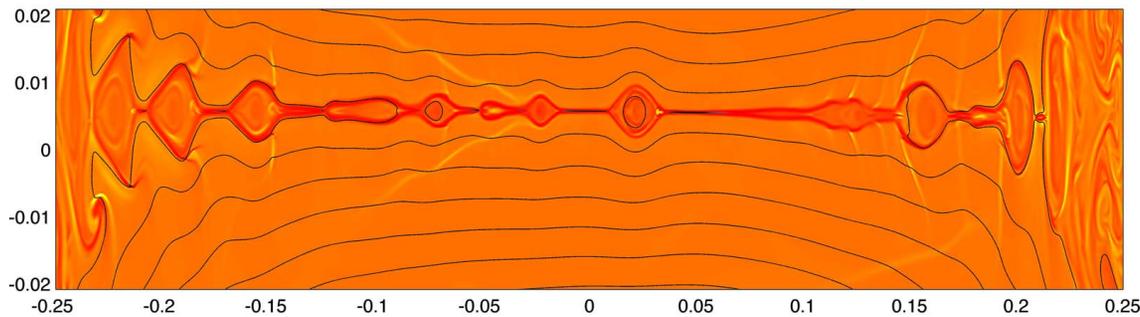


Density: Line ratio
 $(L2-L1)/9=v1$
 $(L3-L2)/70=v2$
 Assume $V1 \sim V2$
 Te and V can be inverted.



Sweet-Parker .vs. Petschek RX

Bhattacharjee+, 2009



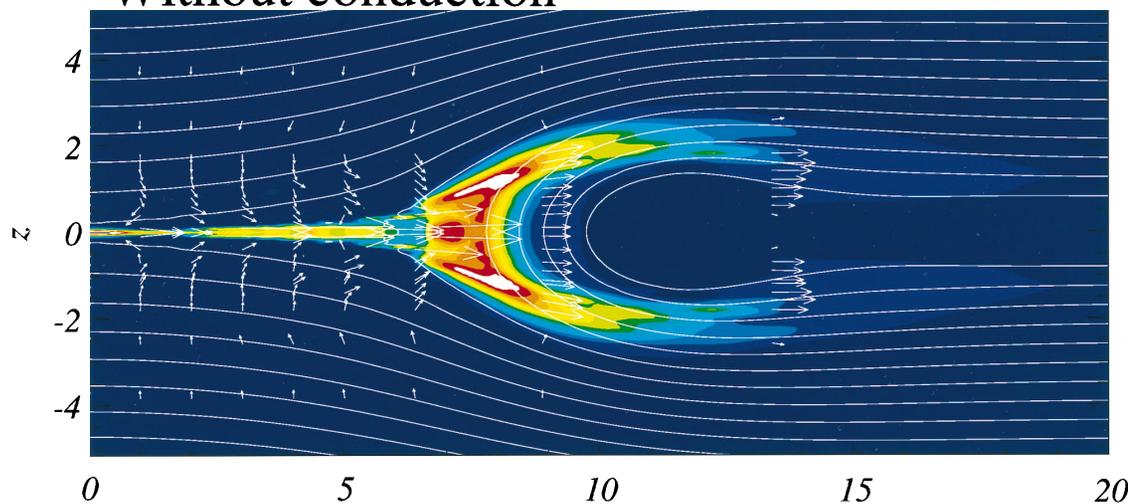
Sweet-Parker like RX

**Heating is localized
inside CS**

Yokoyama&Shibata, 1997

Without conduction

→ = 5.



Petschek RX

**Heating region is larger
by Slow-mode Shock etc.**

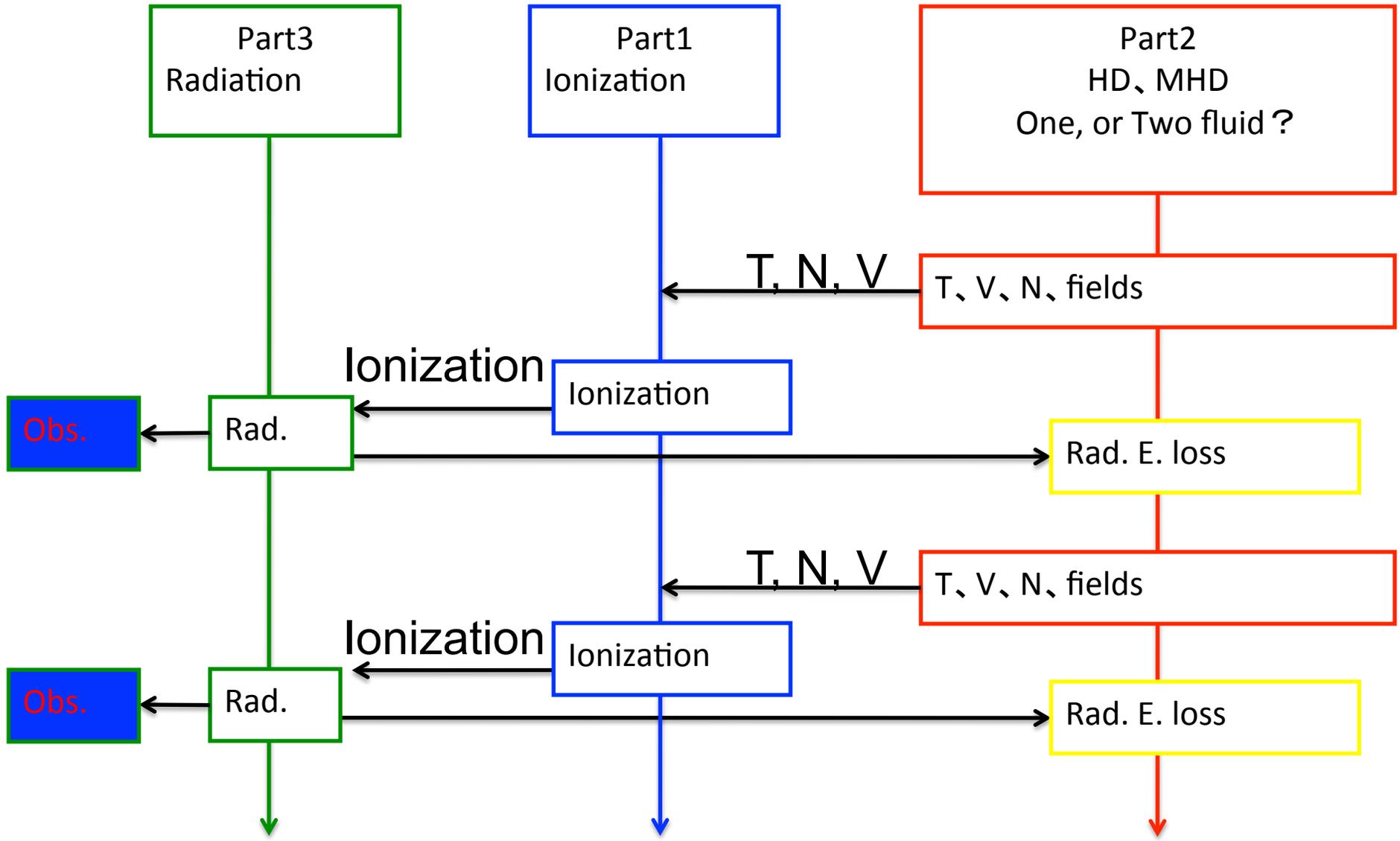
まとめ

- Solar-Cでは格段にeffective areaが大きくなる
- 高時間分解能で観測が可能になる
- 多波長での分光観測
- 迷光・散乱光等のノイズを極力軽減



- 電離過程から加熱の履歴(時間)を診断する事を目指す
- Forward modeling または inversionから短い時間スケールの現象を診断可能に！

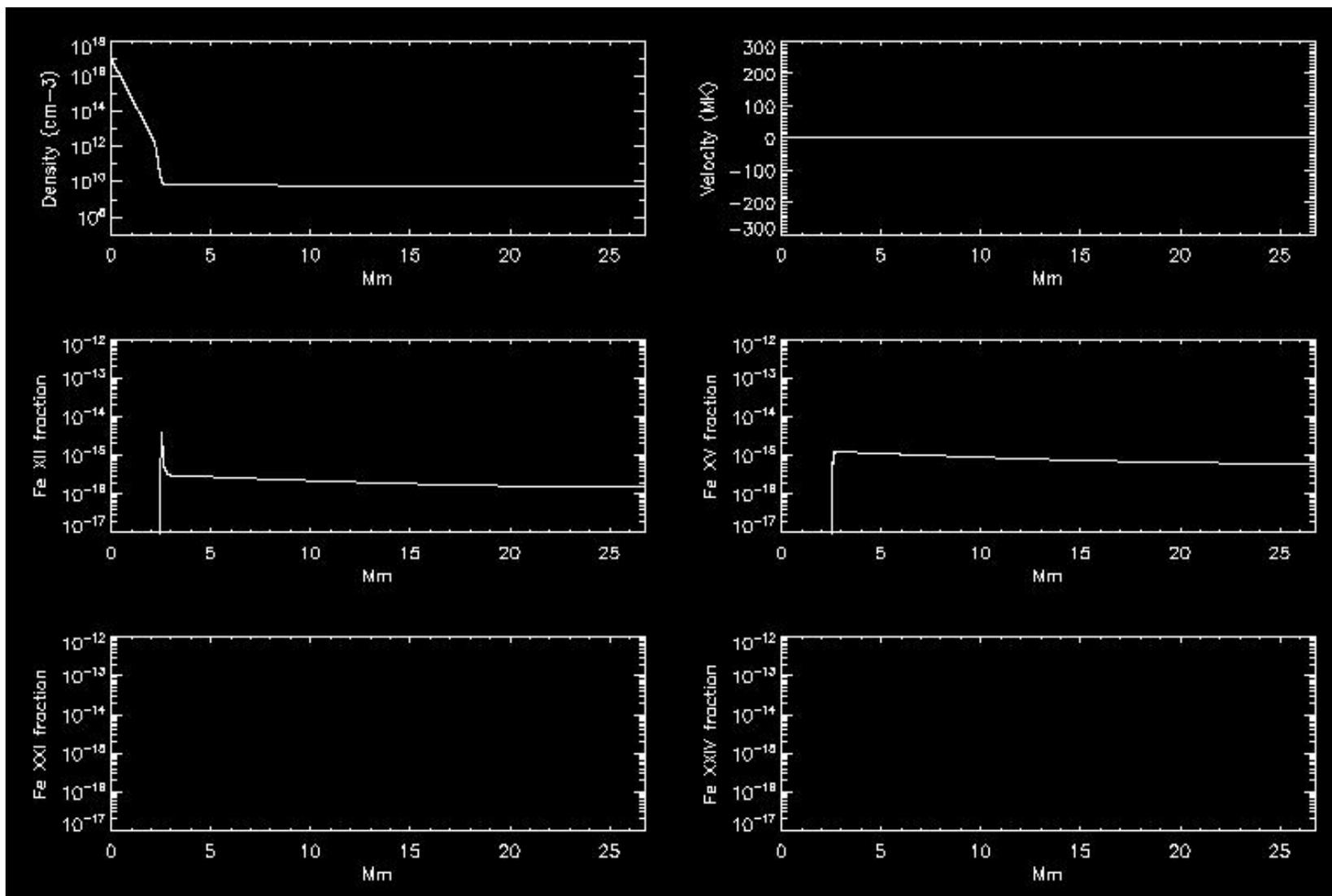
Strategy to solve



電離非平衡計算結果

初期条件: 電離平衡

点線: 電離平衡
実線: 電離非平衡



FeXII

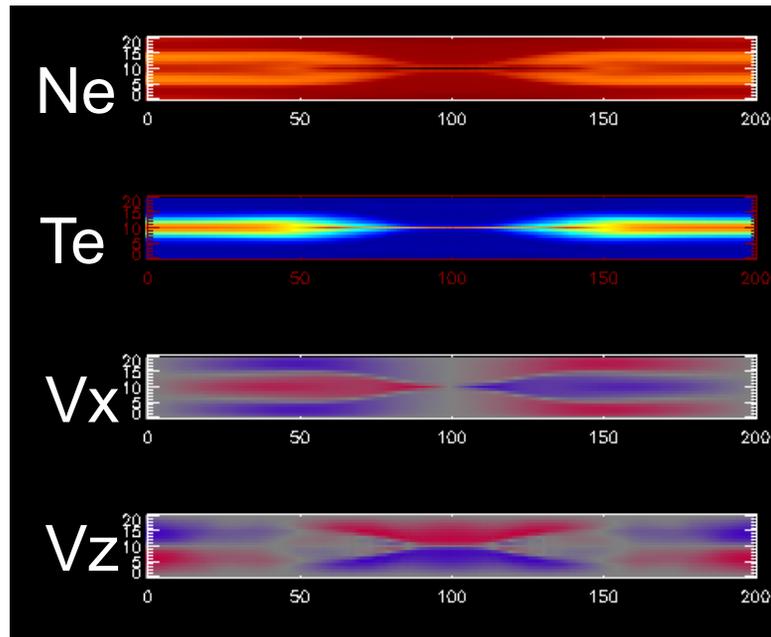
FeXV

FeXXI

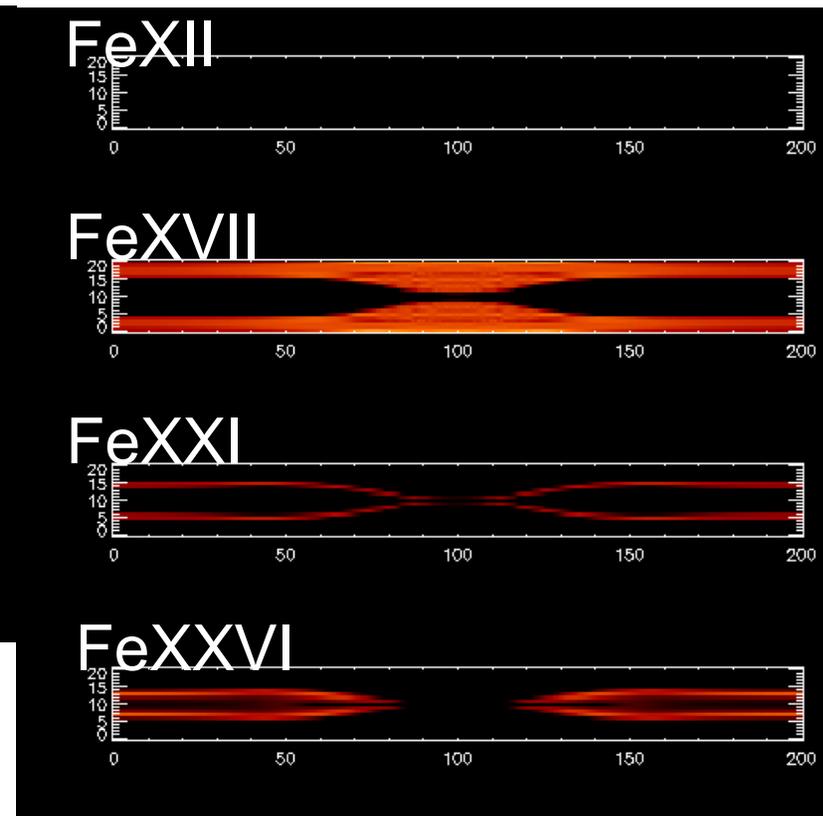
FeXXIV

RX 2D calculation + Time dependent ionization

MHD



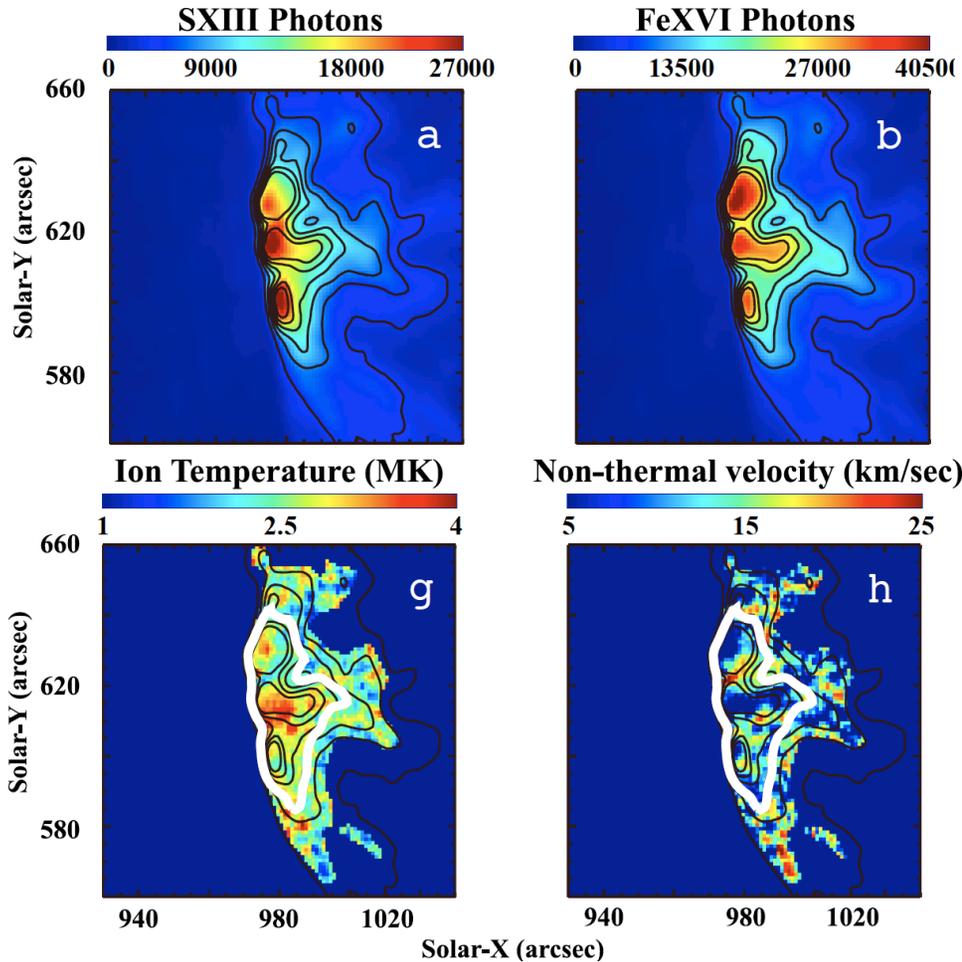
Ionization



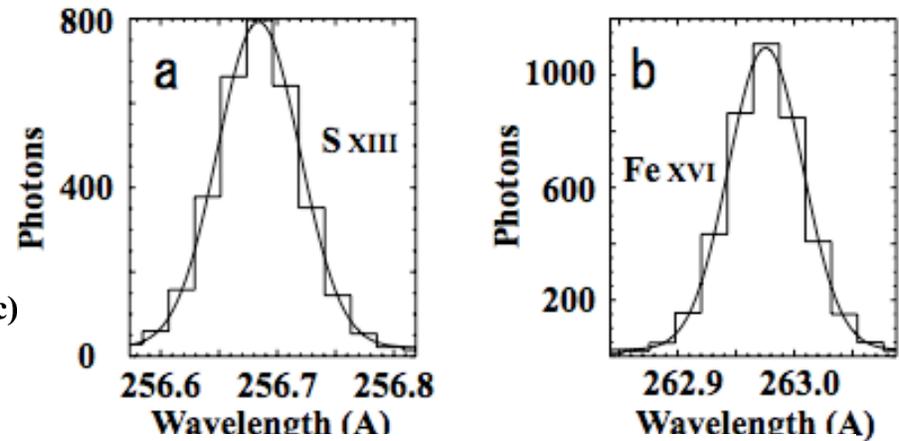
We have to improve our code in some points
(e.g., numerical diffusion).

Coronal Heating : Observation

Ion Temperature



$$W_{obs} = \sqrt{W_I^2 + 4 \log 2 \left(\frac{2k_B T_{ion}}{M} + \xi^2 \right)},$$



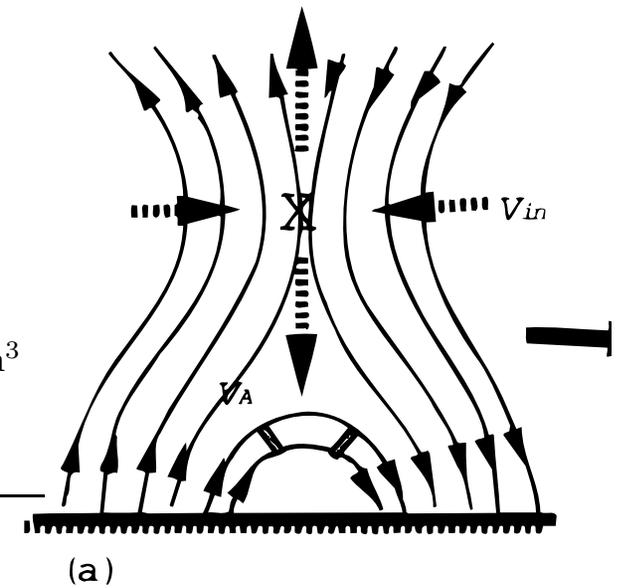
$$T_{ion} = \frac{\widehat{W}_1^2 - \widehat{W}_2^2}{8k_B \log 2} \frac{M_1 M_2}{M_2 - M_1},$$

$$\xi^2 = \frac{M_2 \widehat{W}_2^2 - M_1 \widehat{W}_1^2}{4 \log 2 (M_2 - M_1)},$$

Imada et al., APJL 2009

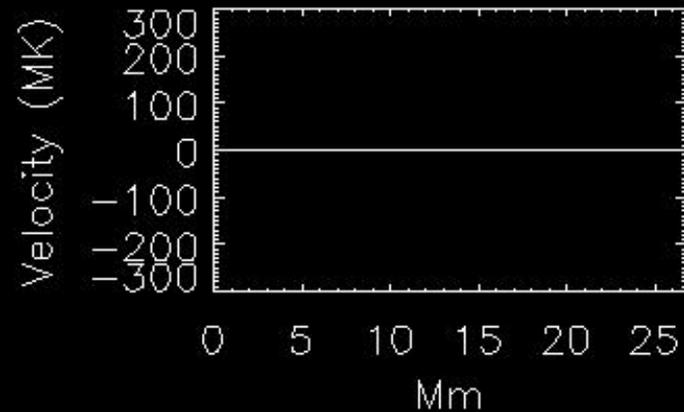
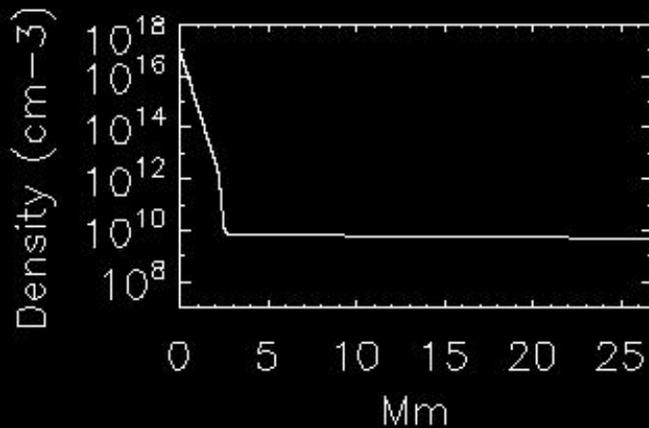
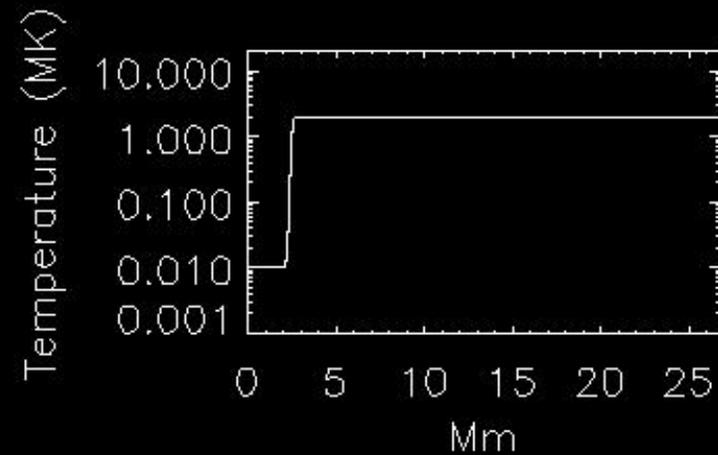
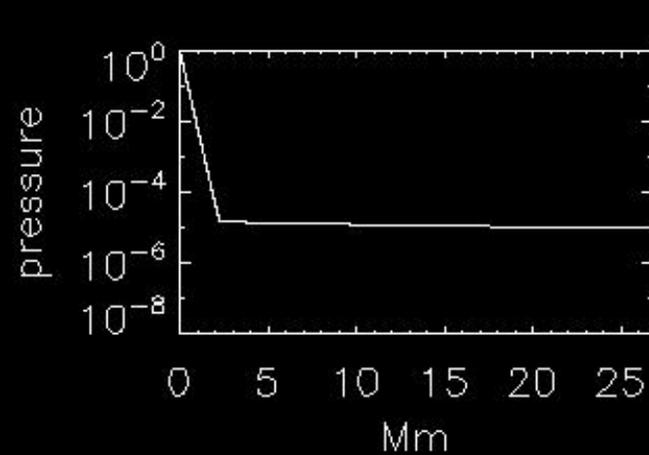
彩層蒸発計算 CANS

パラメータ	変数	無次元値	有次元値
ループ半長	L	130	26000 km
遷移層高さ	x_{tr}	12.5	2500 km
コロナ温度	T_{cor}	200	2 MK
フレア加熱	H_{f0}	5×10^{-4}	$3 \text{ erg cm}^{-3} \text{ s}^{-1}$
フレア範囲	w_f	30	6000 km
フレア時間	τ_f	12	240 s
熱伝導強度	κ_0	3×10^{-11}	10^{-6} cgs
冷却強度	Λ_0	10^9	$8 \times 10^{-22} \text{ erg s}^{-1} \text{ cm}^3$
冷却基準温度	T_{cl}	20	$2 \times 10^5 \text{ K}$
冷却臨界密度	n_{cl}	10^{-5}	10^{12} cm^{-3}
光球温度	T_0	1	10^4 K
光球密度	ρ_0	1	10^{17} cm^{-3}
光球圧力スケール長	\mathcal{H}_0	1	200 km
光球音速	C_{S0}	1	10 km/s
光球音波横断時間	$\tau_0 \equiv \mathcal{H}_0 / C_{S0}$	1	20 s
光球重力	g_0	$1/\gamma$	270 m/s^2

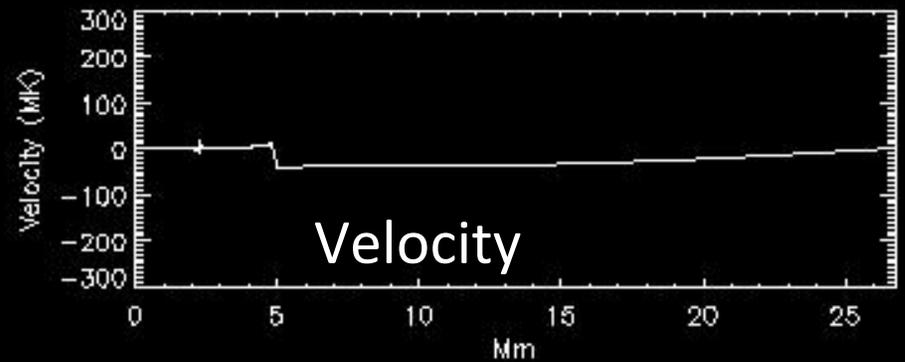
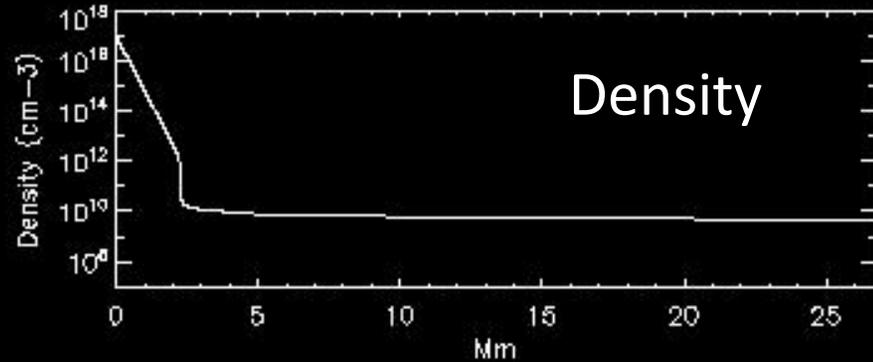


26Mm

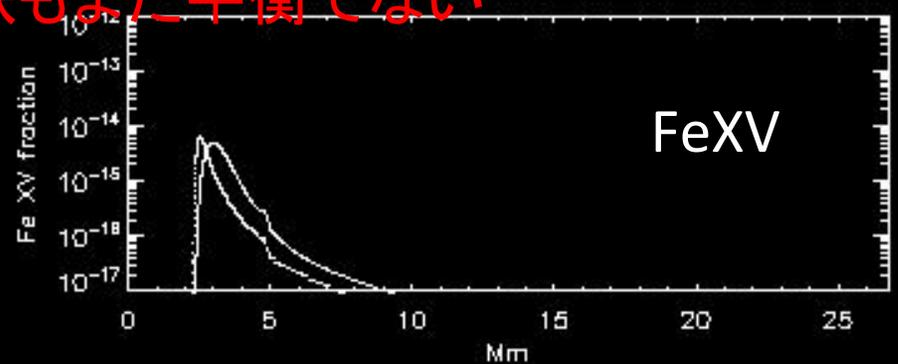
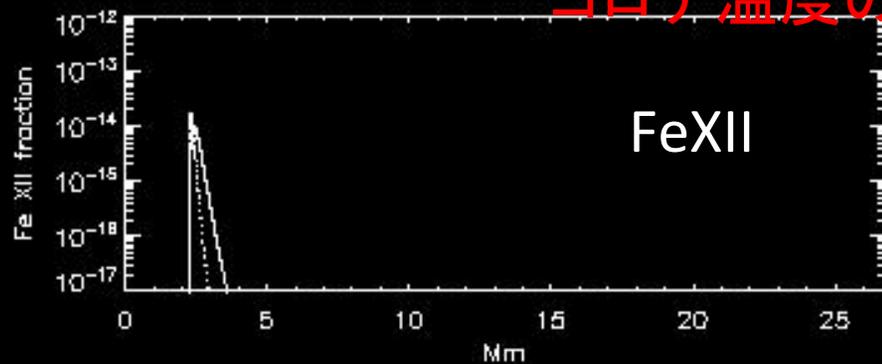
彩層蒸発計算 (CANS-1DHD)



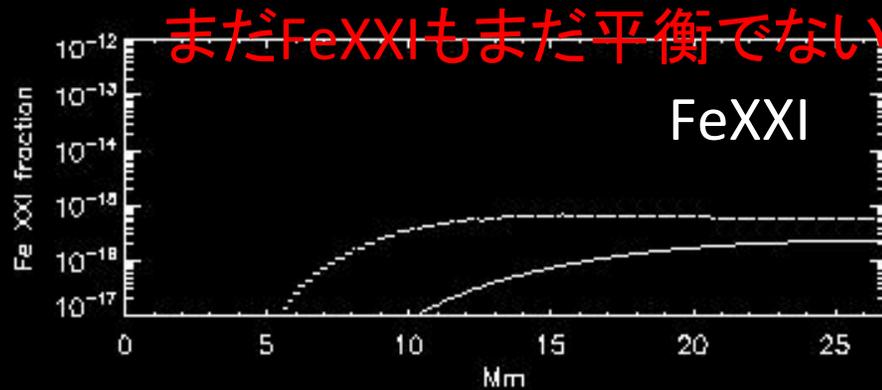
開始から20秒後



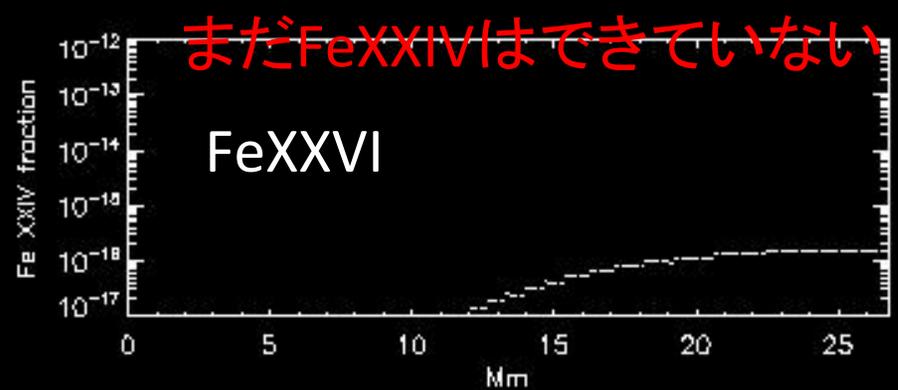
コロナ温度の鉄もまだ平衡でない



まだFeXXIもまだ平衡でない



まだFeXXIVはできていない



鉄イオン別の上下フラックス

初期条件: 電離平衡

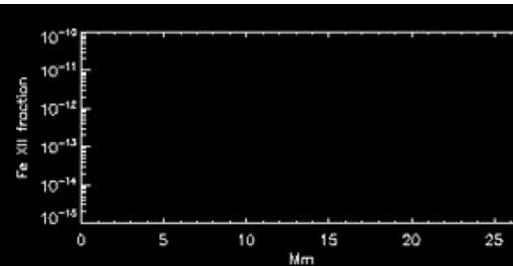
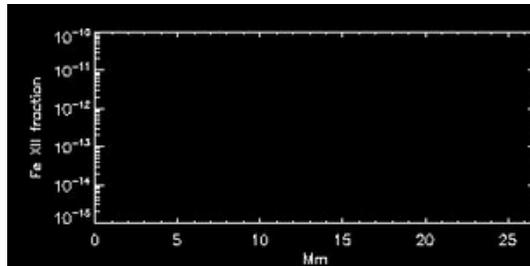
Upward

Downward

点線: 電離平衡

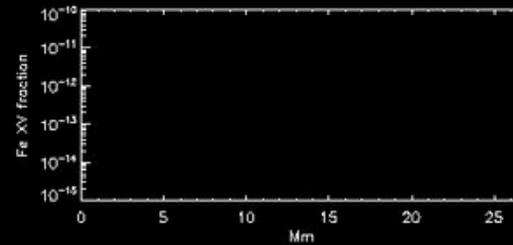
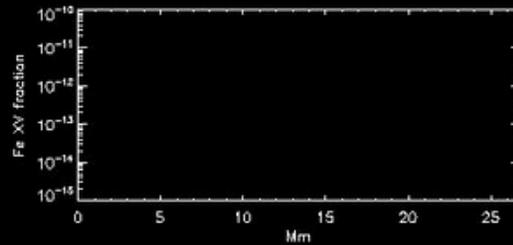
実線: 電離非平衡

FeXII Blue



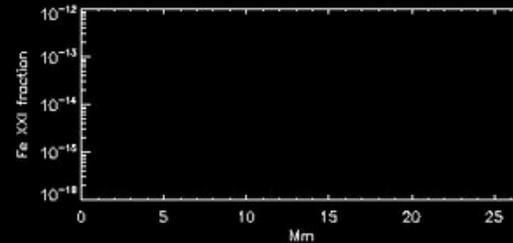
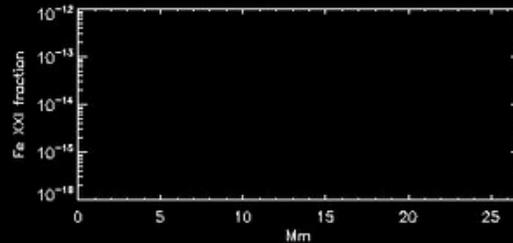
FeXII Red

FeXV Blue



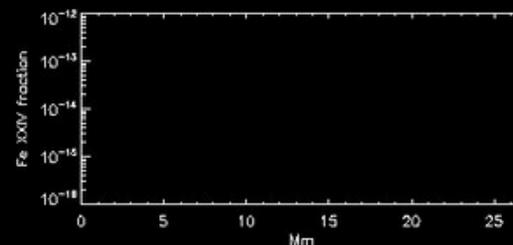
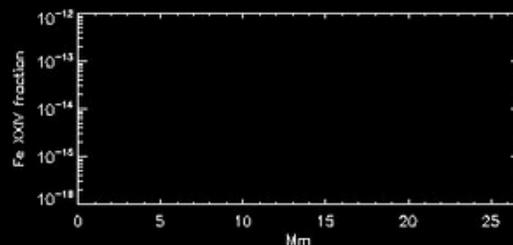
FeXV Red

FeXXI Blue



FeXXI Red

FeXXIV Blue



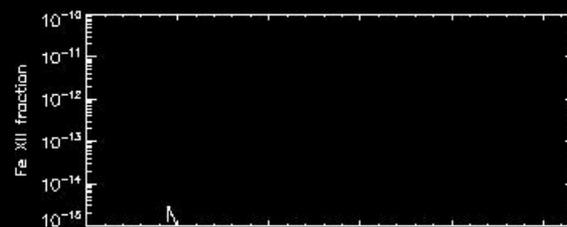
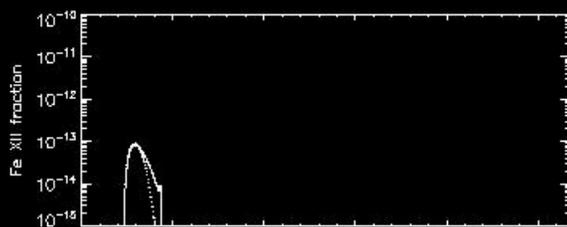
FeXXIV Red

開始から17秒後

Upward

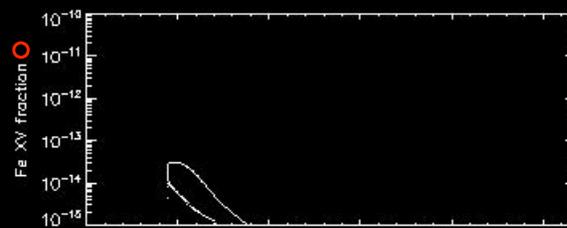
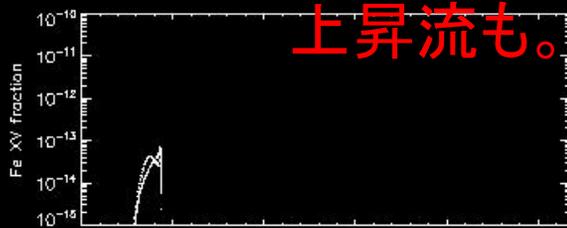
Downward

FeXII Blue



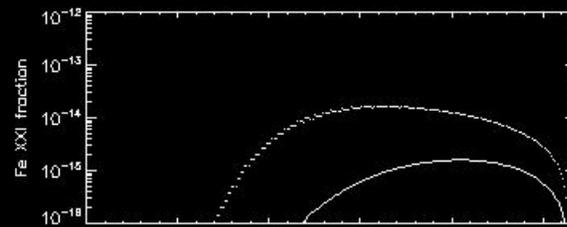
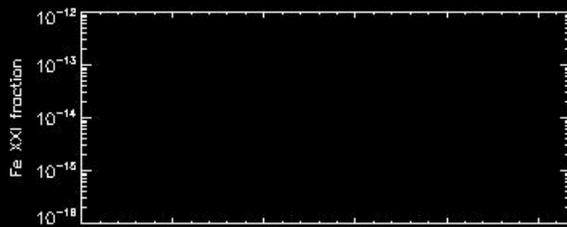
FeXII Red

FeXV Blue



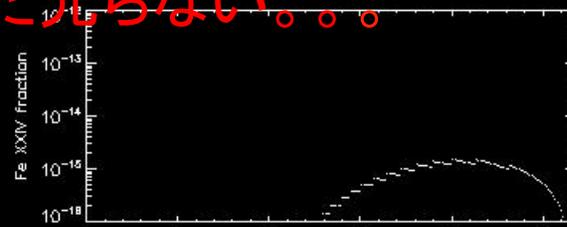
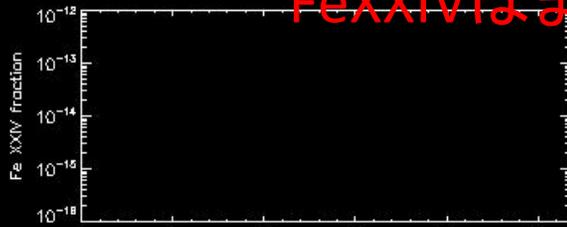
FeXV Red

FeXXI Blue



FeXXI Red

FeXXIV Blue



FeXXIV Red

FeXVで下降流が出ている

上昇流も。。。○

FeXXIVはまだ光らない。。。○

まとめと今後の展望

- 電離非平衡＋彩層蒸発(1DHD)の計算は可能になった
- 近年のEISの分光観測によってFeXV等で impulsive phase に $\sim 50\text{km/sec}$ 程度の下降流が観測されている
- 電離非平衡計算＋流体計算によって再現を試みた結果、FeXVで下降流を作る事は可能だが、定量的には説明困難
- 熱伝導速度飽和やエネルギーインプットの仕方の違い等の可能性も考える必要が
- Solar-Cに向けて、Forwardモデリングを完成させ、フレアでのエネルギー解放を議論できるように