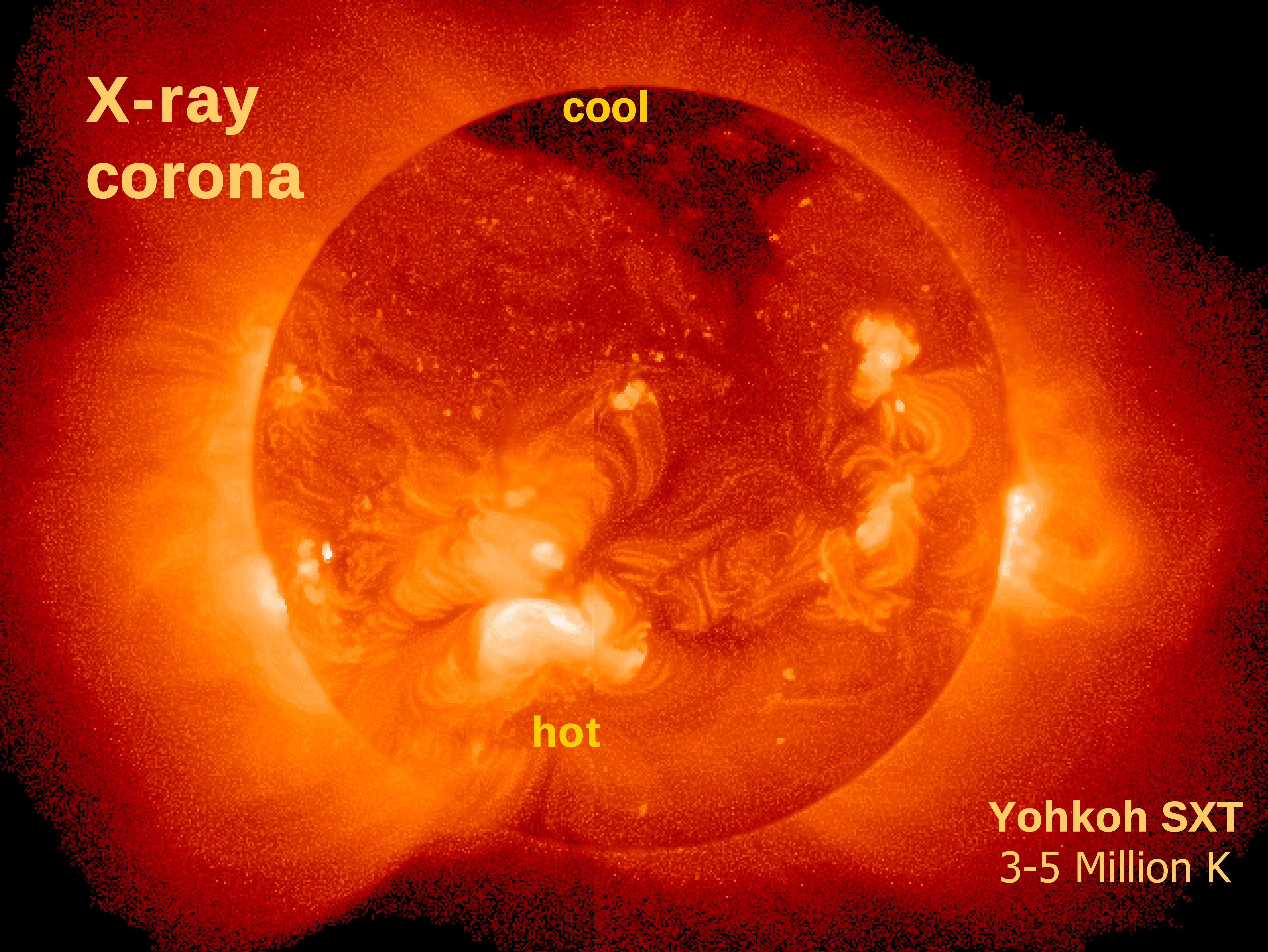
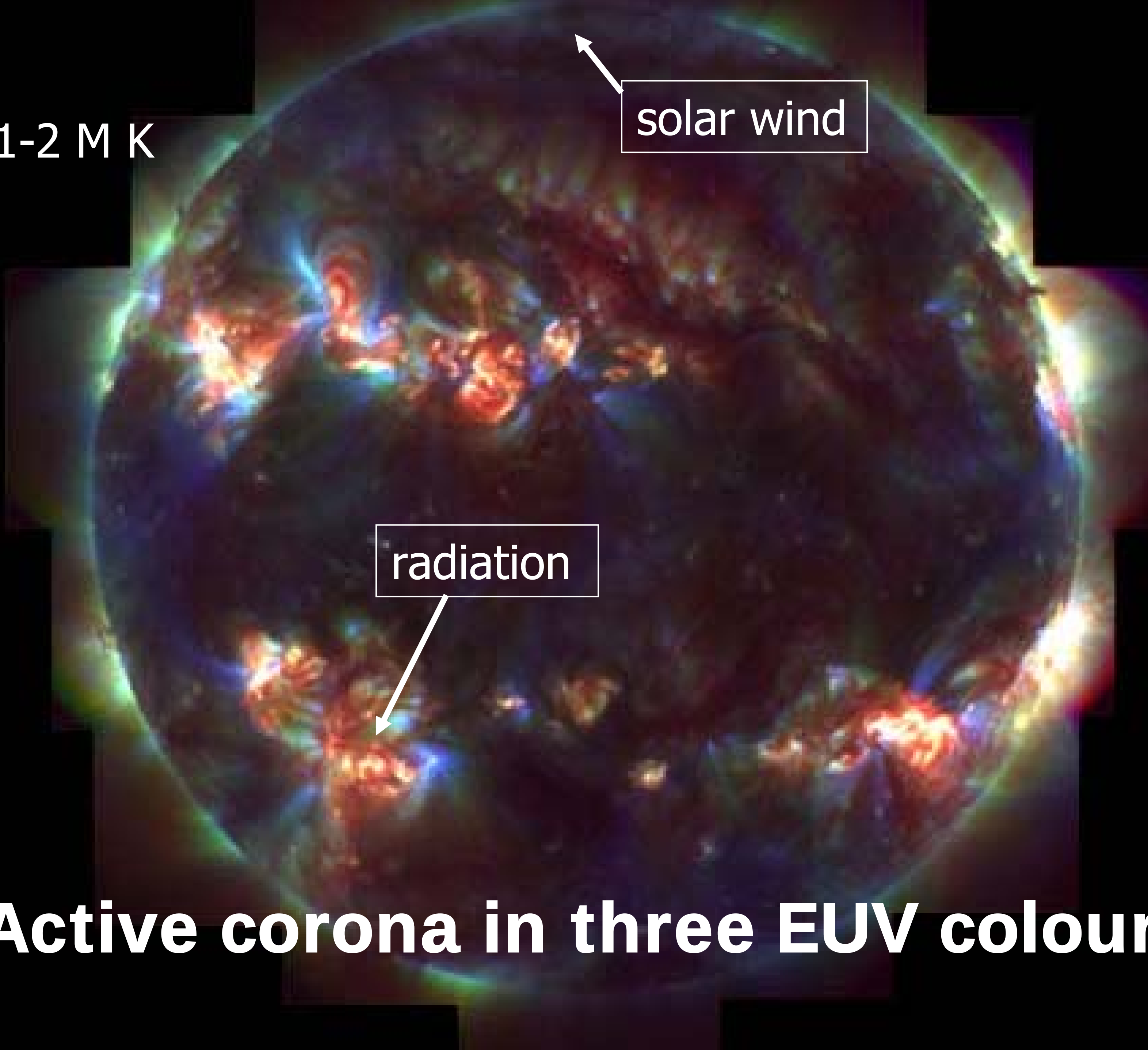
Coronal heating and energetics

- Magnetic structures in the solar corona
- Coronal heating, what does it mean?
- Flares and coronal cooling
- Observations of MHD waves in loops
- Dissipation processes in the corona
- Oscillations of coronal loops



X-ray
corona
cool
hot
Yohkoh SXT
3-5 Million K

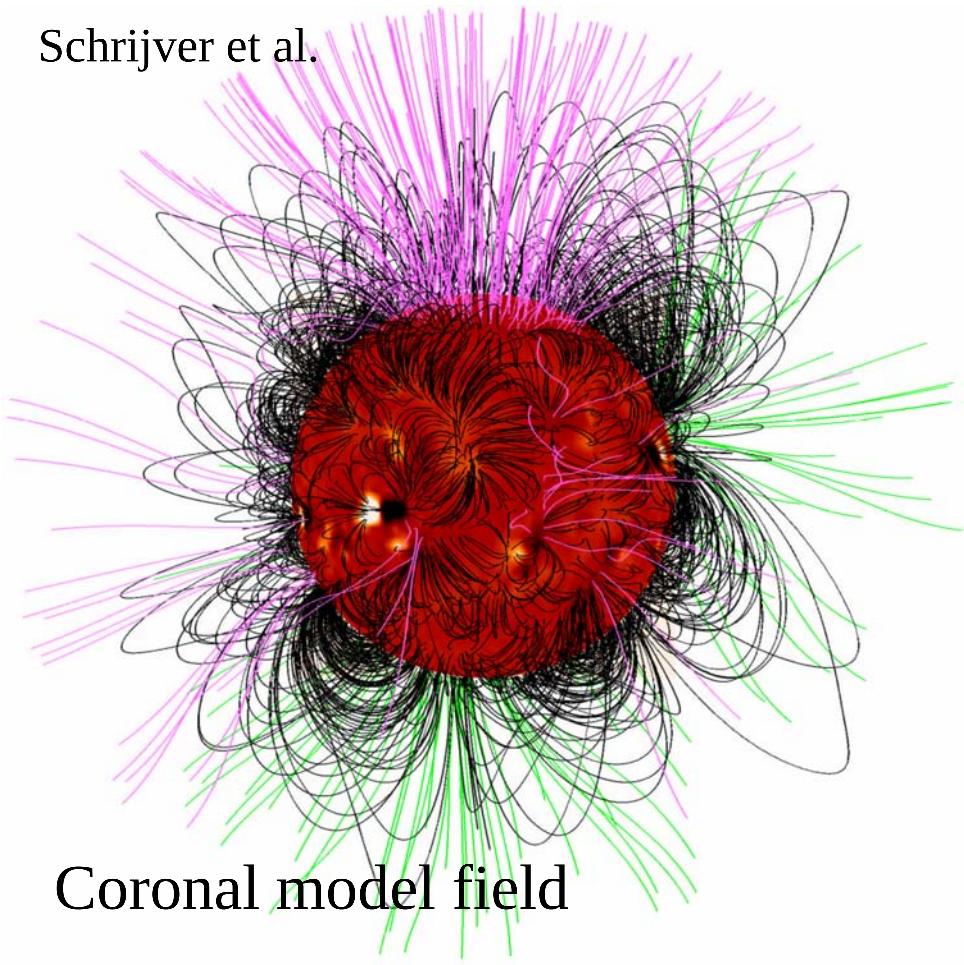


Active corona in three EUV colours

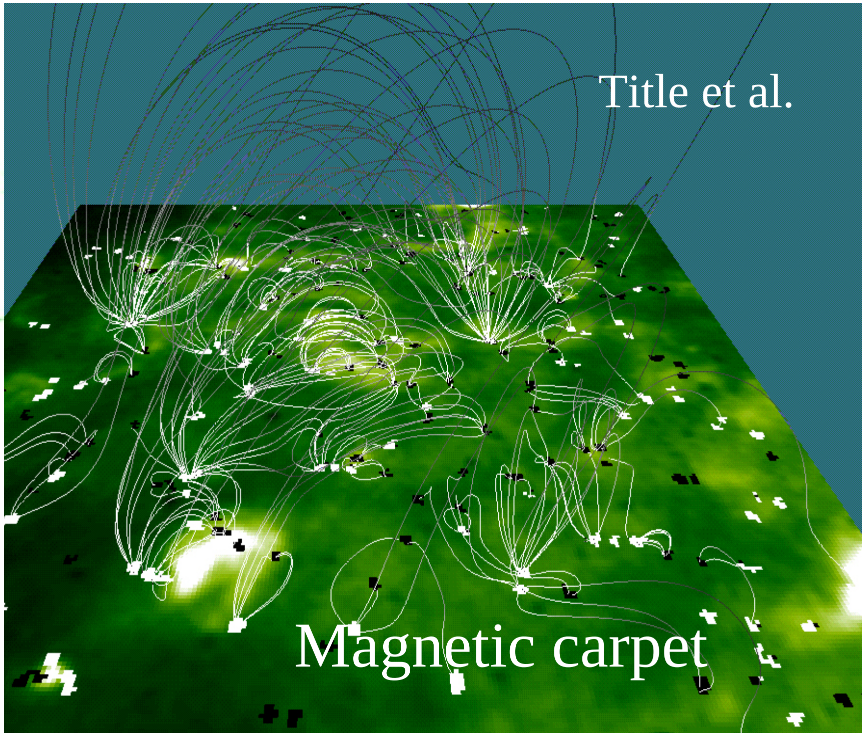
Key player: coronal magnetic field

Modelling by extrapolation (Potential, force-free, MHD)

Schrijver et al.



- **Closed loops and streamers**
- **Coronal funnels and holes**
- **Magnetic transition region (network)**



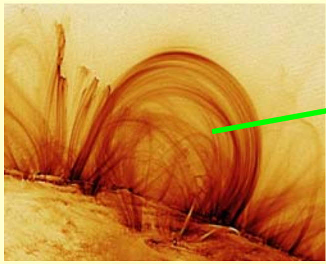
Coronal heating - an unsolved problem

Why?

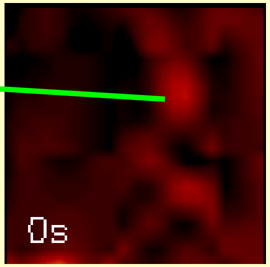
Facing complexity and variability:

- Solar corona is non-uniform and highly structured
- Corona varies in time (magnetic activity cycle)
- Temporal and spatial changes occur on all scales
- Corona is far from thermal (collisional) equilibrium
- Coronal processes are dynamic and often nonlinear

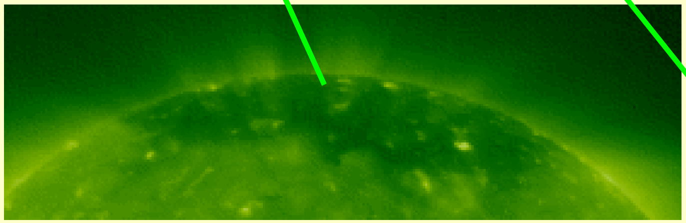
Coronal heating: a buzzword



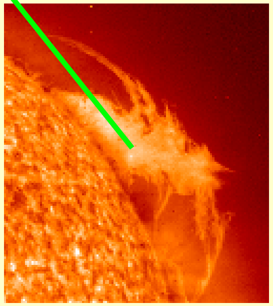
Coronal heating?



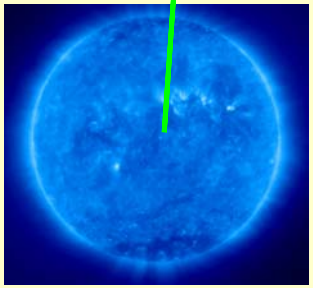
closed magnetic loops are observed at a wide range of temperatures



Small brightenings at a range of wavelenths



polar plumes are observed at “coronal” temperatures in open magnetic structure, the coronal holes



“diffuse” corona radiating at 2 MK is not confined to “bright” loops

special energy requirements in cool (10^4 K) prominence

Time and space dependent

Energy balance in the corona

Coronal loops:

Energy balance mainly between radiative cooling, mechanical heating and heat conduction

$$V \cdot \nabla s = ds/dt|_R + ds/dt|_M + ds/dt|_C$$

Coronal holes:

Energy balance mainly between solar-wind losses and mechanical heating

$$\nabla \cdot (F_K + F_G + F_M) = 0$$

$$F_M = \rho V_{sw} (V^2_{sw} + V^2_{\infty})/2 \qquad V_{\infty} = 618 \text{ km/s}$$

Energetics of the solar corona

Parameter (erg $cm^{-2}s^{-1}$)	**Coronal hole (open)**	**Active region (closed)**
Chromospheric radiation loss	$4\ 10^6$	$2\ 10^7$
Radiation	10^4	$< 10^6$
Conduction	$5\ 10^4$	$10^5 – 10^6$
Solar wind	$(5\text{-}10)\ 10^5$	$(< 10^5)$

Photosphere: $6.3\ 10^{10}$ erg $cm^{-2}\ s^{-1}$

10^5 erg $cm^{-2}\ s^{-1}$
$= 100\ W\ m^{-2}$

Coronal heating, what does it mean?

Mechanical and magnetic energy:

- Generation/release
- Transport/propagation
- Conversion/dissipation

- Magnetoconvection, restructuring of fields and magnetic reconnection
- Magnetohydrodynamic + plasma waves, shocks
- Ohmic + microturbulent heating, radiative cooling, resonance absorption

Collisional heating rates

Chromosphere: $N = 10^{10}\ \mathrm{cm}^{-3}$ $h_G = 400$ km. Perturbations:
$\Delta L = 200$ km, $\Delta B = 1$ G, $\Delta V = 1$km/s, $\Delta T = 1000$ K.

Viscosity: (erg $\mathrm{cm}^{-3}\ \mathrm{s}^{-1}$) $H_V = \eta\,(\Delta V/\Delta L)^2 = 2\ 10^{-8}$

Conduction: $H_C = \kappa\,\Delta T/(\Delta L)^2 = 3\ 10^{-7}$

Joule: $H_J = j^2/\sigma = (c/4\pi)^2(\Delta B/\Delta L)^2/\sigma = 7\ 10^{-7}$

Radiative cooling: $C_R = N^2\Lambda(T) = 10^{-1}\ \mathrm{erg\ cm}^{-3}\ \mathrm{s}^{-1}$

Smaller scale, $\Delta L \approx 200$ m, required

$\lambda_{\mathbf{Coll}} \approx$ **1 km**

Effective Reynolds number must be smaller by $10^6 - 10^8$

Requirements on coronal transport

Coronal plasma beta is low, $\beta \approx 0.1 - 001$, --> strongly magnetized particles, which freely move parallel to **B**.

Coulomb collisional transport, then diffusion coefficient:

$$\mathbf{D_c = (\rho_e)^2 \nu_e \approx 1\ m^2 s^{-1}}$$

with electron Larmor radius, $\rho_e \approx$ 25 cm, and collision frequency, $\nu_e \approx 10\ s^{-1}$; $\rho_p \approx$ 10 m, $B \approx 1$ G, $n_e \approx 10^8\ cm^{-3}$.

Enhanced transport requires „anomalous“ processes: Waves, turbulence, drifts, flows, stochastic fields....., ν_e -> Ω_e.

Litwin & Rosner, ApJ **412**, 375, 1993

Loop switch-on time: $\tau \approx$ 1-10 s. Is the current channel scale comparable to transverse loop dimension, $a \approx 1000$ km? Cross diffusion time: $t_D = a^2/D \approx 10^{12}$ s.

Coronal heating mechanisms

Wave (AC) mechanisms (generation, propagation, non-uniformity)

- Sound waves, shocks (barometric stratification), turbulence
- Magnetoacoustic (body, surface), Alfvén (resonance absorption)
- Plasma (dispersive) waves (Landau damping), ion-cyclotron waves

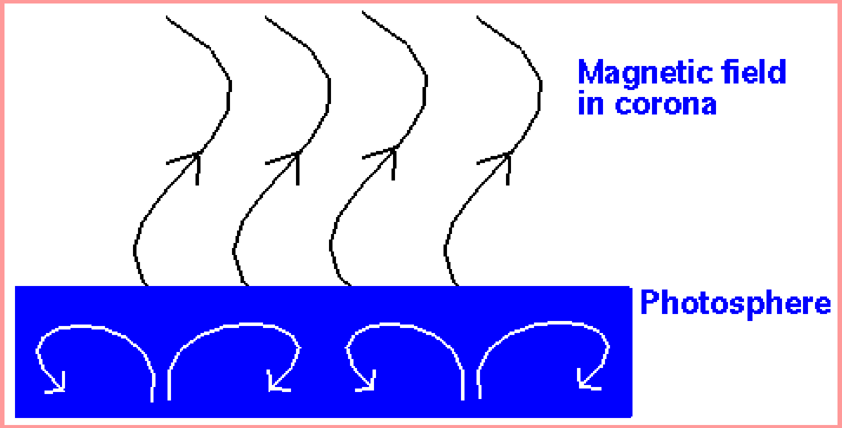
Current sheet (DC) mechanism (formation of sheets, flux emergence)

- Quasi-static current sheet formation in force-free fields
- Dynamic sheet formation driven by flux emergence
- Field-aligned currents (ohmic and anomalous resistivity)

Heating by micro/nano/pico flares (magnetic field reconnection)

- Thermalization of energetic particles (Bremsstrahlung: radio to X-rays)
- Reconnection driven by colliding magnetic flux

MHD wave heating



Coronal magnetic field rooted down in turbulent photosphere

=> Waves!

- Generation of MHD waves driven by magneto-convection
- Phase mixing due to gradients
- Absorption at small scales

Process	Period/s
Alfvèn/fast magnetosonic	< 5
Sound/slow magnetosonic	< 200
Gravity	40
Conduction	600
Radiation	3000
Convection	> 300

Detectability of coronal MHD waves

- **Spatial** (pixel size) and **temporal** (exposure/cadence) **resolution** be less than **wavelengths** and **periods**

- **Spectral resolution** to be sufficient to resolve Doppler shifts and broadenings (best, SUMER, 1-15 km/s)

Spacecraft/Instrument	Spatial Resolution, Minimum pixel size/ arcsec	Temporal resolution, Maximal cadence/ s	Spectral bands
SOHO/EIT	2.6	30	EUV
SOHO/CDS	2	30	EUV
SOHO/UVCS	12	seconds - hours	EUV/FUV/WL
SOHO/SUMER	1	10	EUV/FUV
SOHO/LASCO C1	5.6	60	WL
Yohkoh/SXT	4	a few	SX
Yohkoh/HXT	60	0.2	HX
TRACE	0.5	10	EUV/FUV/WL

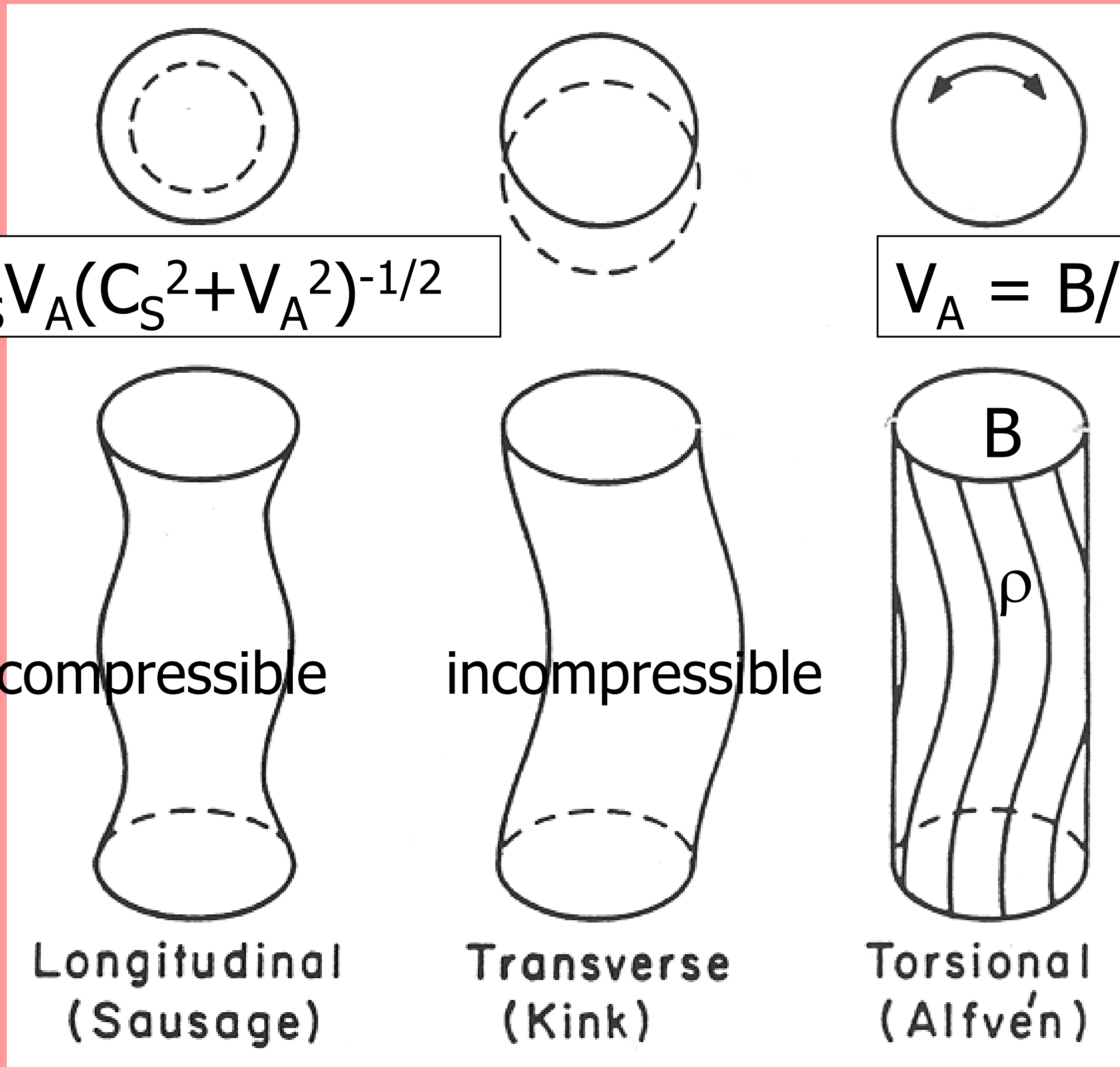
Nakariakov, 2003

Oscillations of magnetic flux tube

$C_T = C_S V_A (C_S^2 + V_A^2)^{-1/2}$

$V_A = B/(4\pi\rho)^{1/2}$

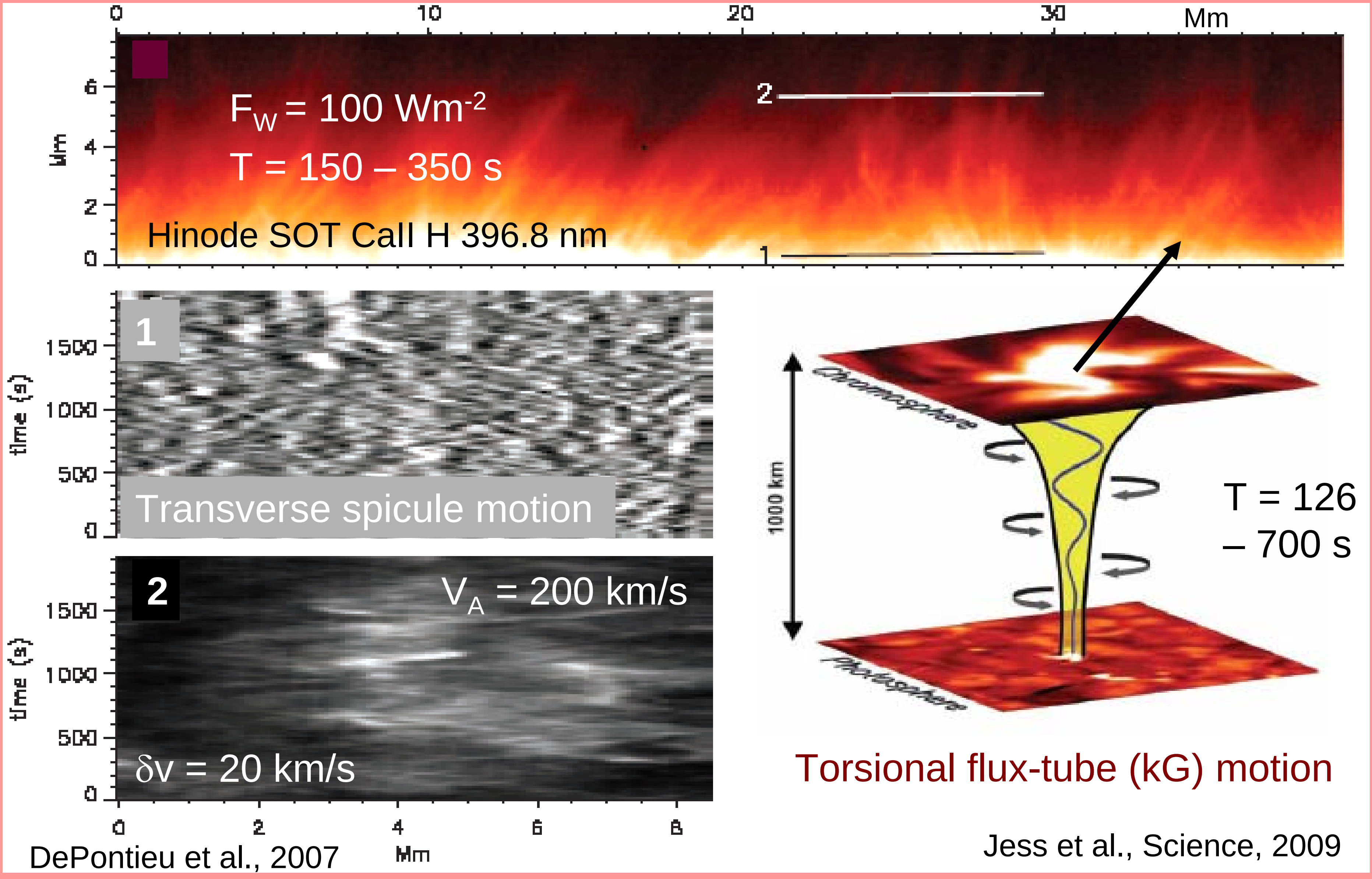
Magnetic and thermal pressure



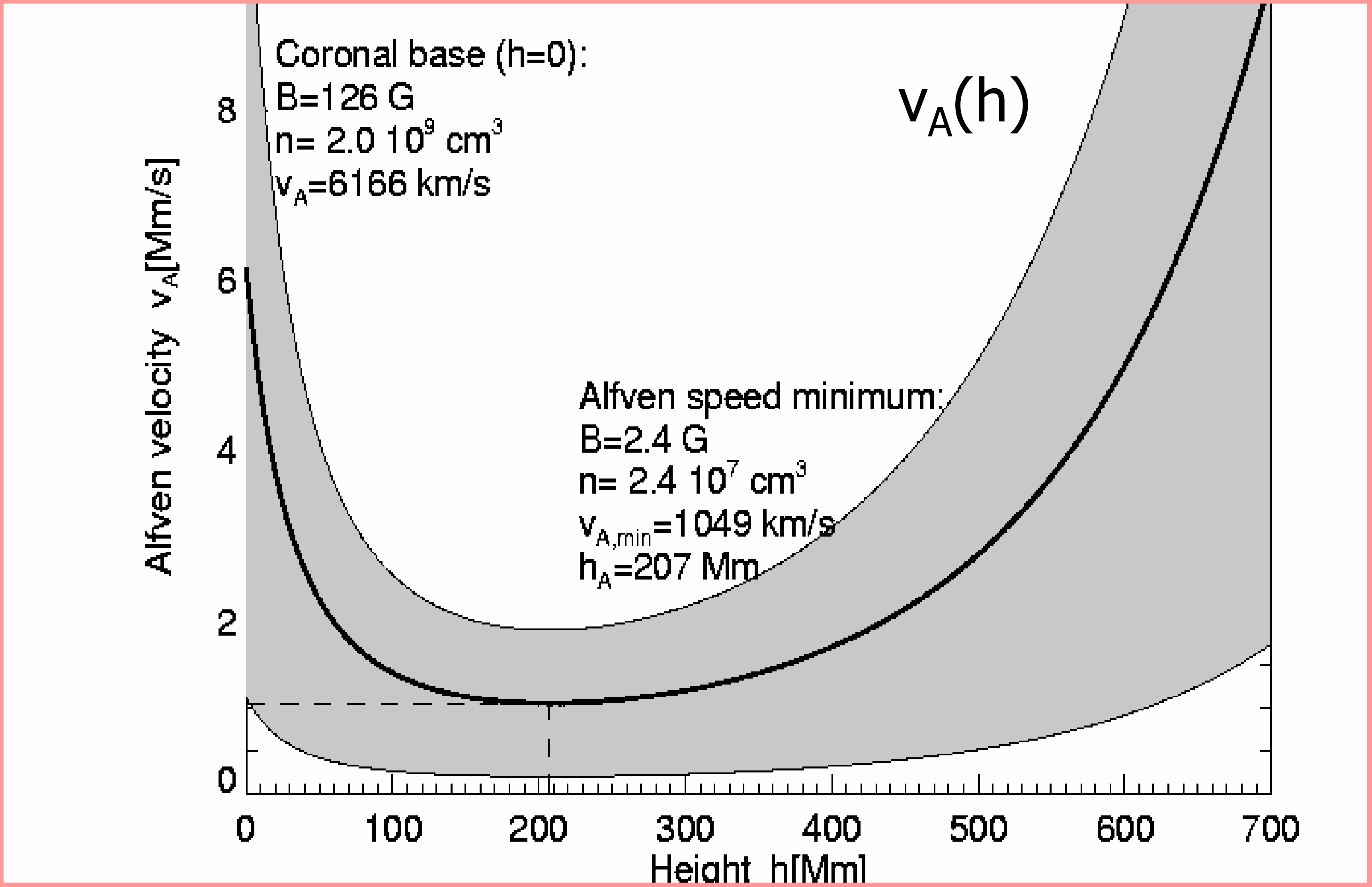
Magnetic curvature force (tension)

Roberts, 1991

Alfvén waves in solar chromosphere

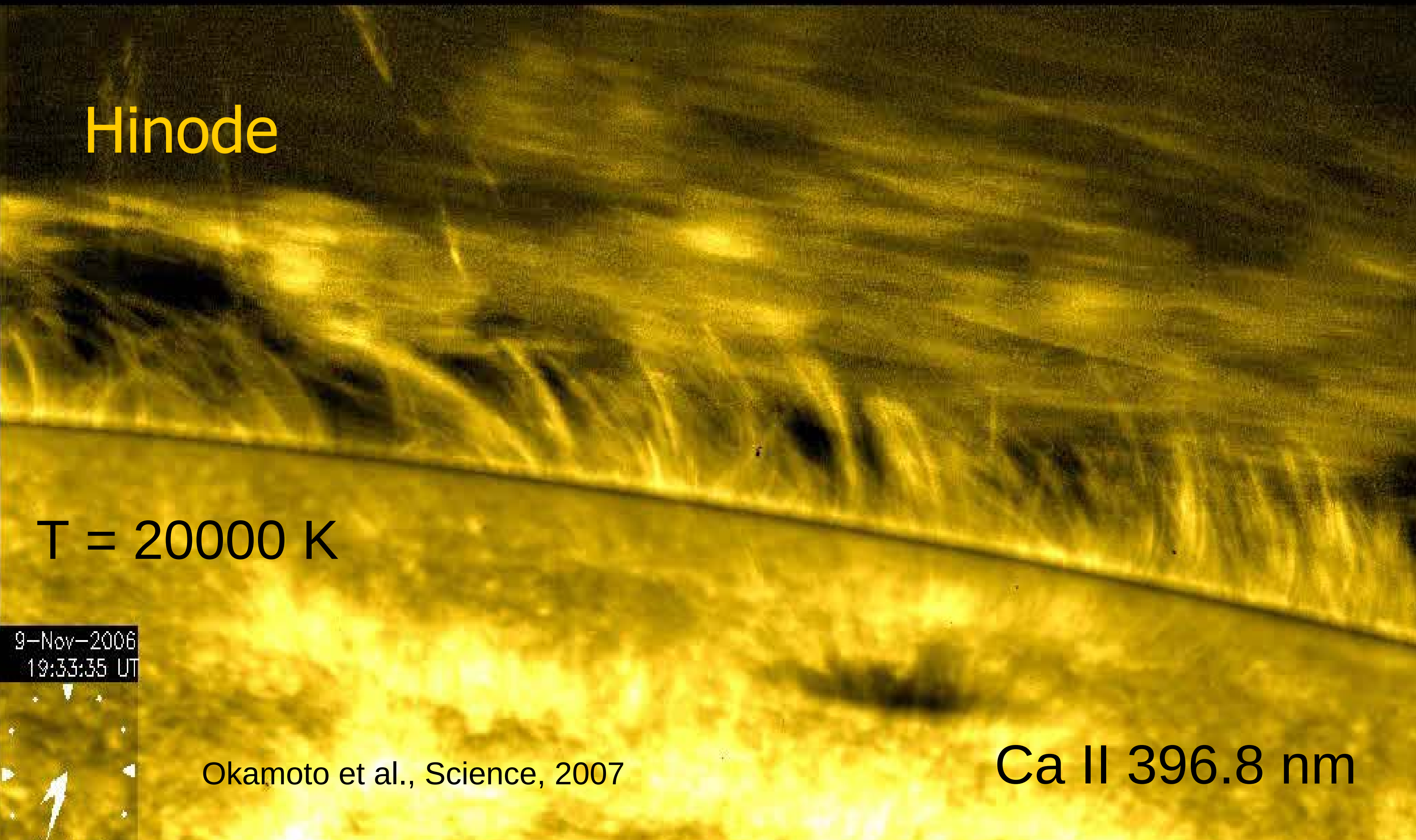


Varying coronal Alfvén speed



Aschwanden, 2004

Alfven waves in prominence



Linear magnetohydrodynamic waves

Background pressure equilibrium:

$$\nabla(p_0 + \frac{B^2}{8\pi}) = 0$$

Coupled linear wave equations (total pressure p_T):

$$\rho_0 \left(\frac{\partial^2}{\partial t^2} - c_A^2 \frac{\partial^2}{\partial z^2} \right) \mathbf{v}_\perp = -\nabla_\perp (\frac{\partial p_T}{\partial t}) \, , \qquad \frac{\partial p_T}{\partial t} = \rho_0 \left(c_A^2 \frac{\partial v_z}{\partial z} - (c_s^2 + c_A^2) \nabla \cdot \mathbf{v} \right)$$

$$\rho_0 \left(\frac{\partial^2}{\partial t^2} - c_t^2 \frac{\partial^2}{\partial z^2} \right) v_z = -(\frac{c_t}{c_A})^2 \frac{\partial}{\partial z} (\frac{\partial p_T}{\partial t}) \qquad p_T = p + \frac{1}{4\pi} \mathbf{B}_0 \cdot \mathbf{B}$$

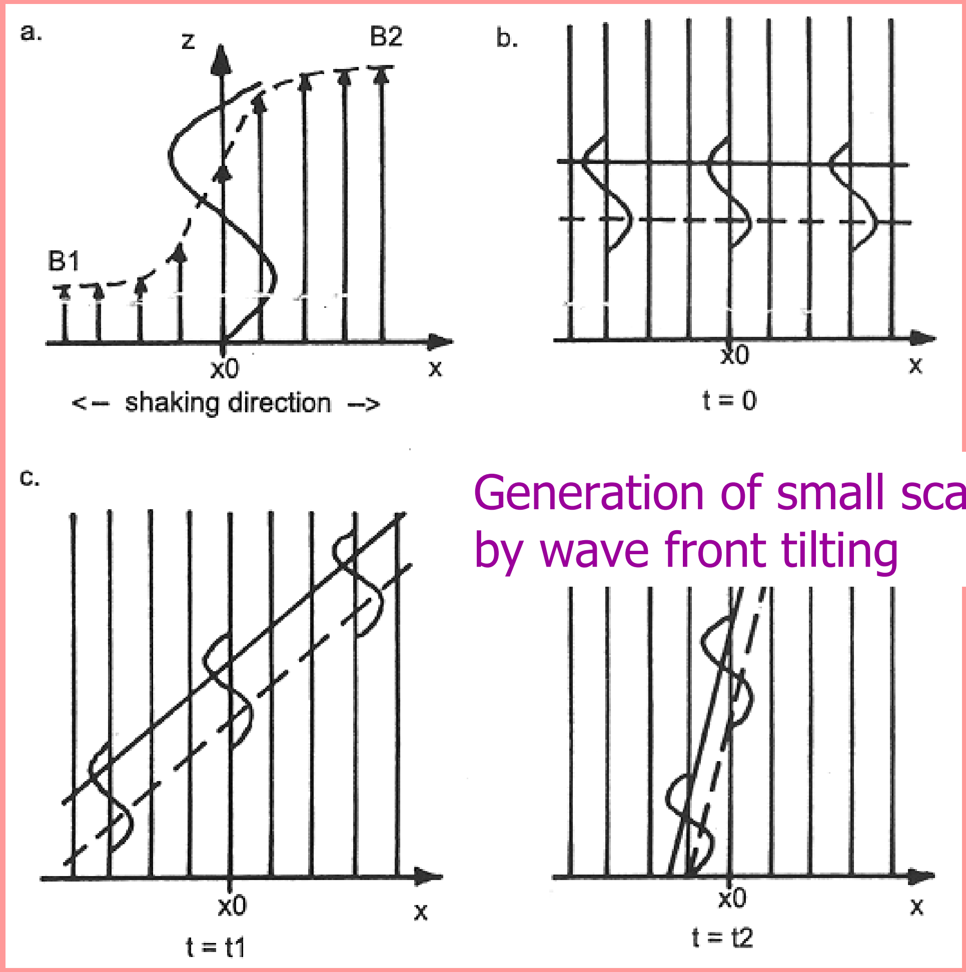
Alfven, sound, and tube wave phase speed:

$$c_A = B_0 / \sqrt{(4\pi\rho_0)} \qquad c_s = \sqrt{\gamma p_0 / \rho_0} \qquad c_t = c_s c_A / \sqrt{c_s^2 + c_A^2}$$

Roberts, 1985

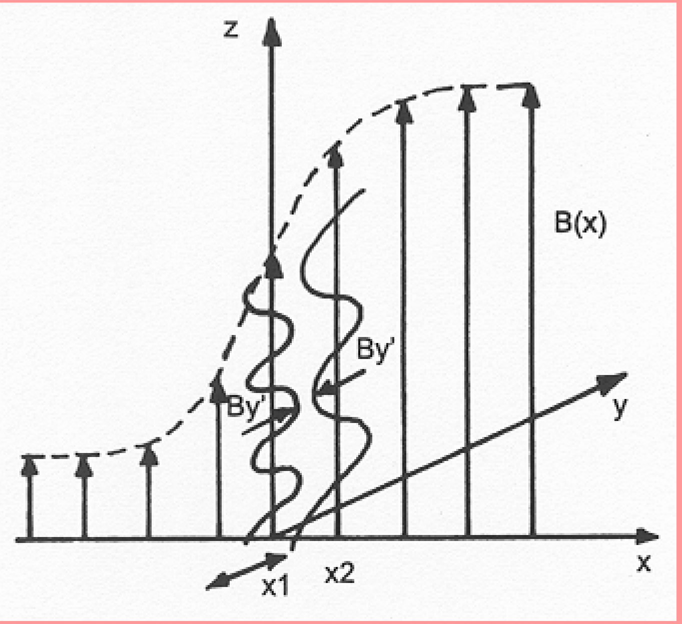
Coronal heating mechanisms I

Resonant absoption of magnetoacoustic surface waves on a field gradient



Generation of small scales by wave front tilting

Phase mixing leads to current sheets and small scale gradients -> dissipation



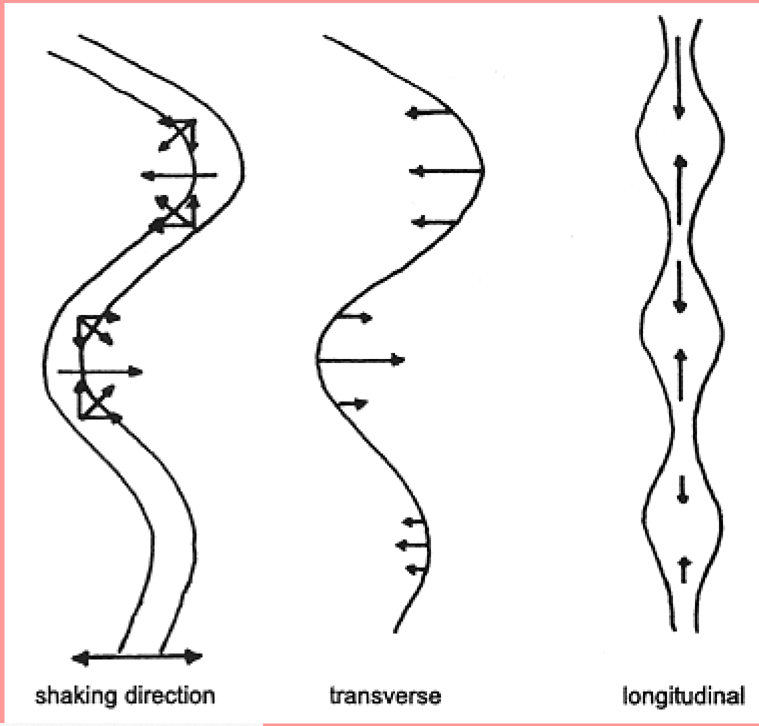
Ulmschneider, 1998

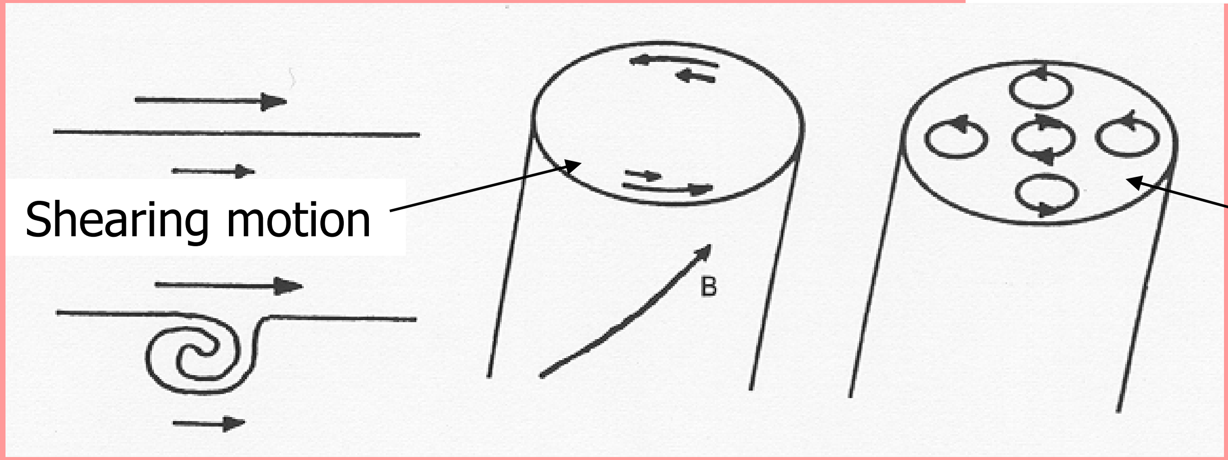
Coronal heating mechanisms II

Pressure equilibrium:
$p_e = p_i + B_i^2/8\pi$

Gas pressure: $p_e \approx 1$ dyn/cm^2
Equipartition field: $B_i \approx 1$ kG

- Generation by turbulence
- Wave mode couplings





Turbulent heating

Decay into smaller vortices or flux tubes

Heyvaerts & Priest, 1983

Coronal heating mechanisms III

Heating by kinetic plasma waves

Absorption of high-frequency waves

Wave generation and transport?

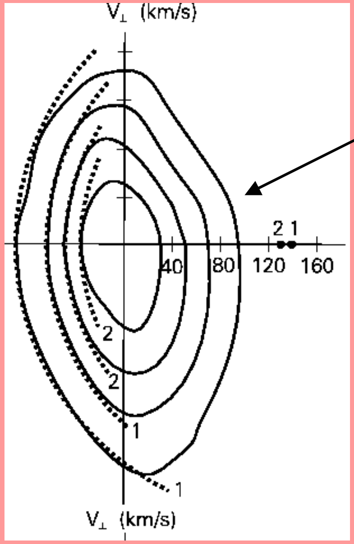
Damping rate: $\gamma/\omega \sim \partial f/\partial v$

- **Landau damping:** $\omega - \mathbf{k} \cdot \mathbf{v} = 0$
- **Cyclotron damping:** $\omega - \mathbf{k} \cdot \mathbf{v} \pm \Omega = 0$

Advantage: Processes occur at small scales, near the ion inertial length or gyroperiod,

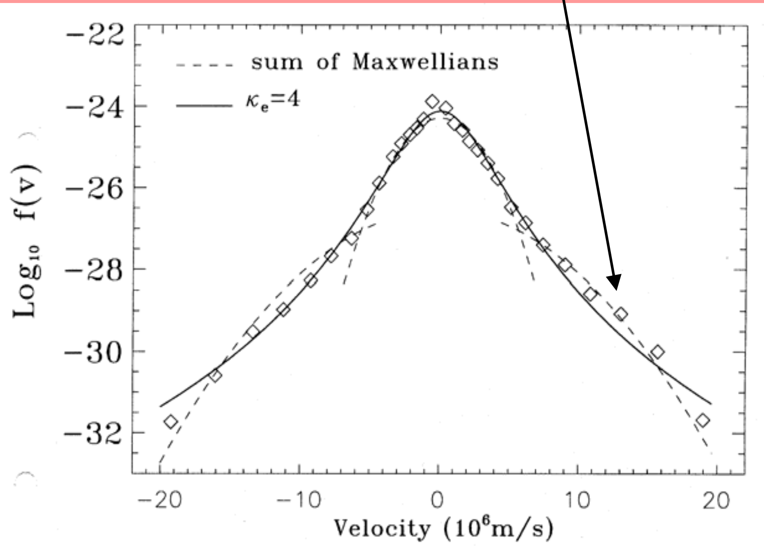
$$\ell = V_A/\Omega\,,\quad \tau = 2\pi/\Omega$$

Problem: Velocity distribution are unknown; in-situ evidence for non-thermal features ->



Anisotropic protons in solar wind

electrons with suprathermal tails



Detectability of plasma waves

- **Spatial** (pixel size) and **temporal** (exposure/cadence) **resolution** be less than **wavelengths** and **periods** **-->** **presently not possible**
- **Spectral resolution** is sufficient to resolve Doppler shifts and broadenings, due to the integrated effects of the unresolved **high-frequeny turbulence** with a line-of-side **amplitude** ξ, which leads to an effective ion temperature:

$$T_{i,eff} = T_i + m_i / (2k_B) < \xi^2 >$$

Shortest scales: **Proton cyclotron wavelength $\approx$ 100 m in CH**

$\lambda_p = 2\pi v_A/\omega_{gp} = 1434$ [km] $(n/cm^{-3})^{-1/2}$, $P_p = 2\pi/\omega_{gp} = 0.66$ [ms] $(B/G)^{-1}$

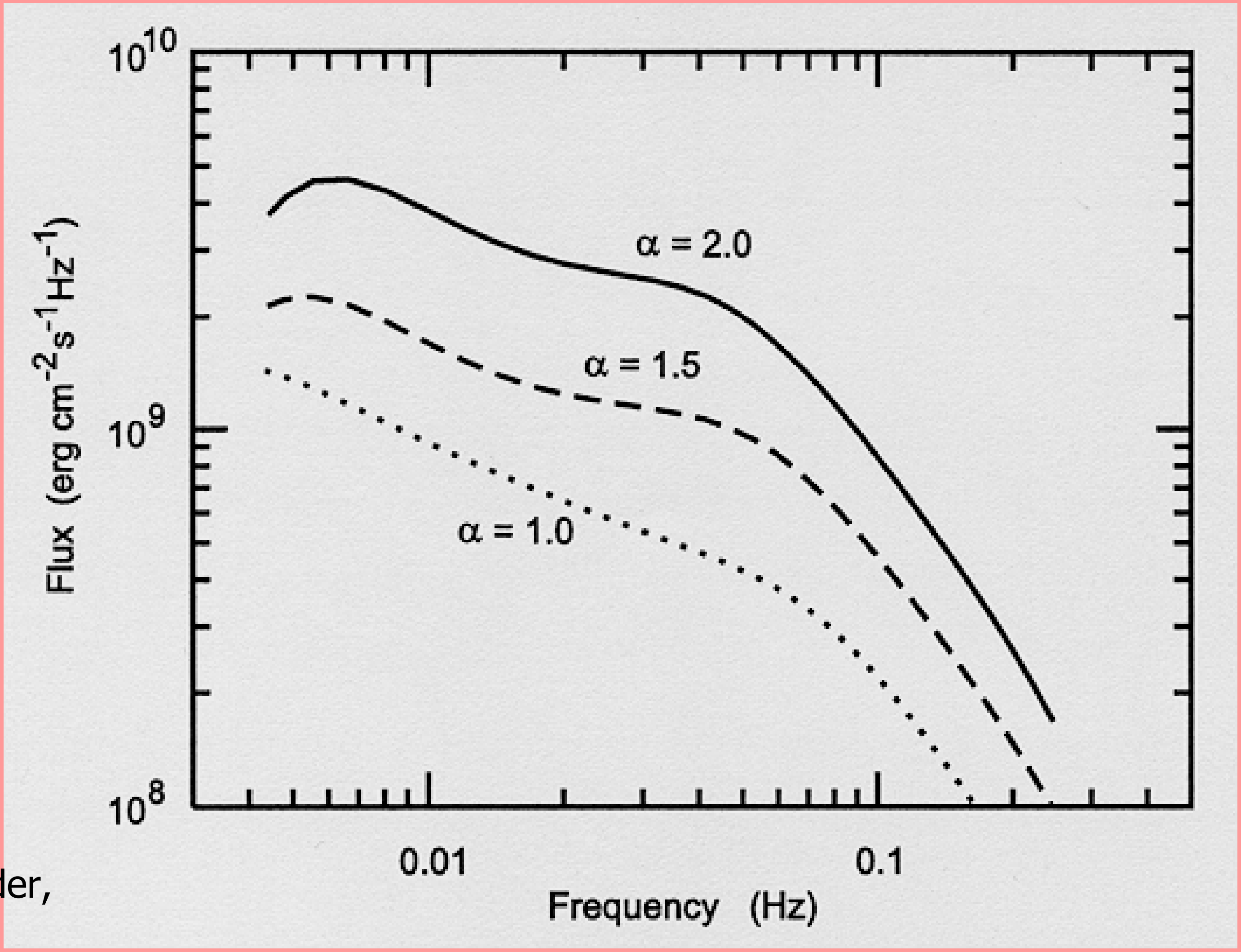
Largest scales: $\lambda < L$ and $P < T$, where L is the **extent of field of view** and T the **duration of observational sequence**.

Wave spectrum generated by turbulent shaking of flux tubes

Here α is the mixing length parameter, with $\lambda = \alpha H$, and barometric scale height H.

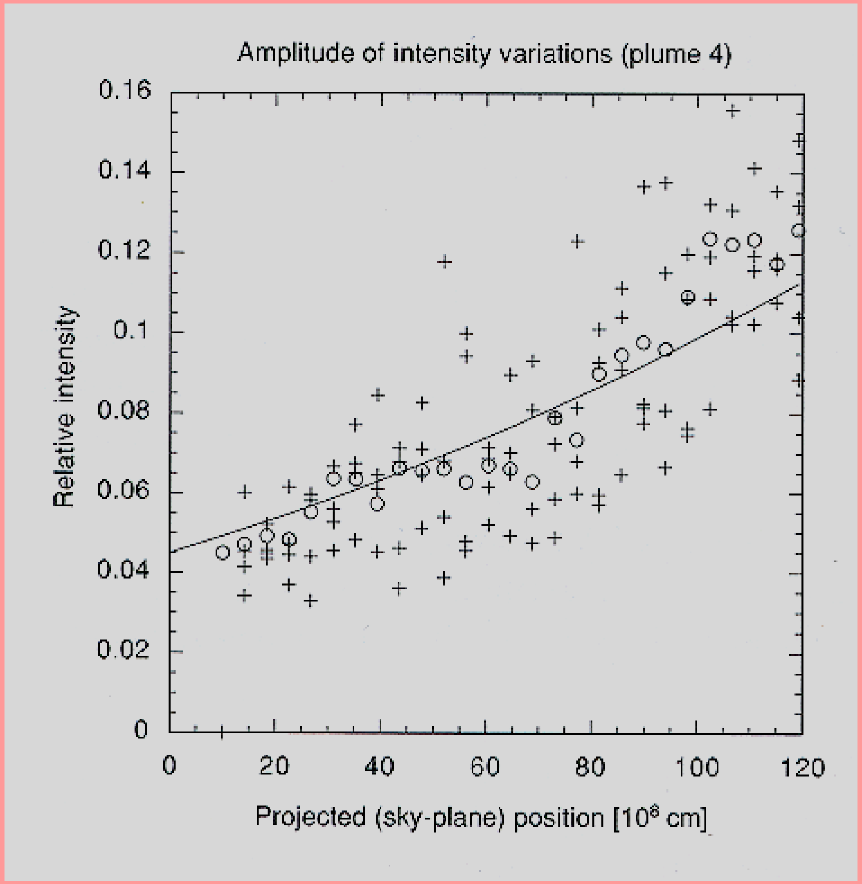
Photosphere: H=300 km.

Thin flux tube oscillations -> torsional Alfvén waves

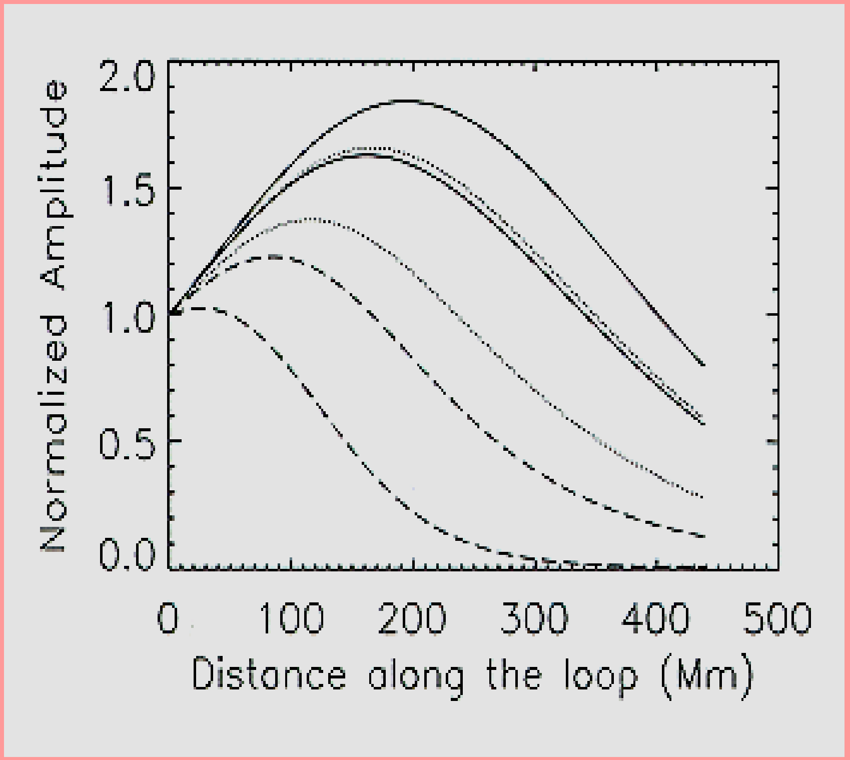


Musielak & Ulmschneider, A&A, **386**, 606, 2002

Wave amplitudes in numerical model



Compressive wave amplitude relative to background in ***open plume*** versus height



Slow magnetosonic wave amplitude versus height, with $\delta V_0 = 0.02\ C_s$, in a coronal ***magnetic loop***

Ofman et al., 1999

Wave steepening

Nakariakov et al., 2000

Coronal cooling, what does it mean?

Heating and cooling varies spatially and temporally!

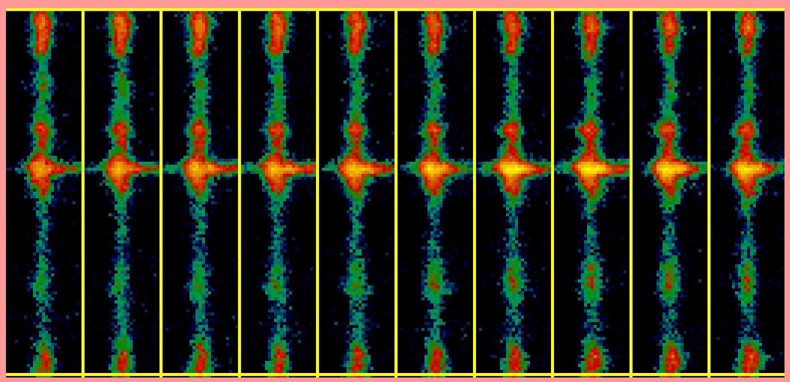
- Radiative cooling: quiet emissions, flares, blinkers, brightenings, in UV, EUV, and X-rays
- Cooling through particles: solar wind, energetic ions and electrons

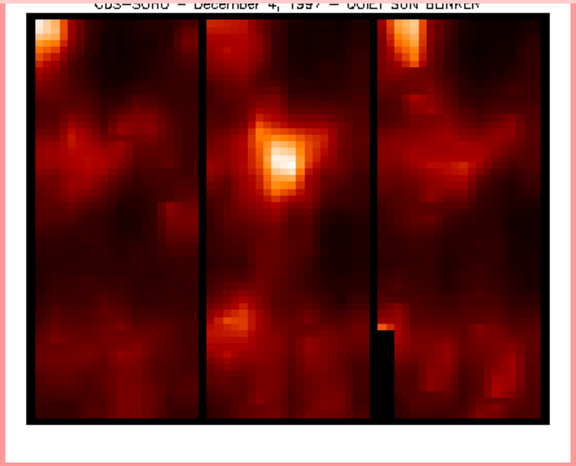
- Dense plasma in magnetic + gravitational confinement
- Dilute plasma escaping on open field lines

Multitude of small brightenings

Active region transient brightenings (SXT), **Explosive events** (SUMER),

EUV brightenings (EIT, TRACE), **Blinkers** (CDS)....





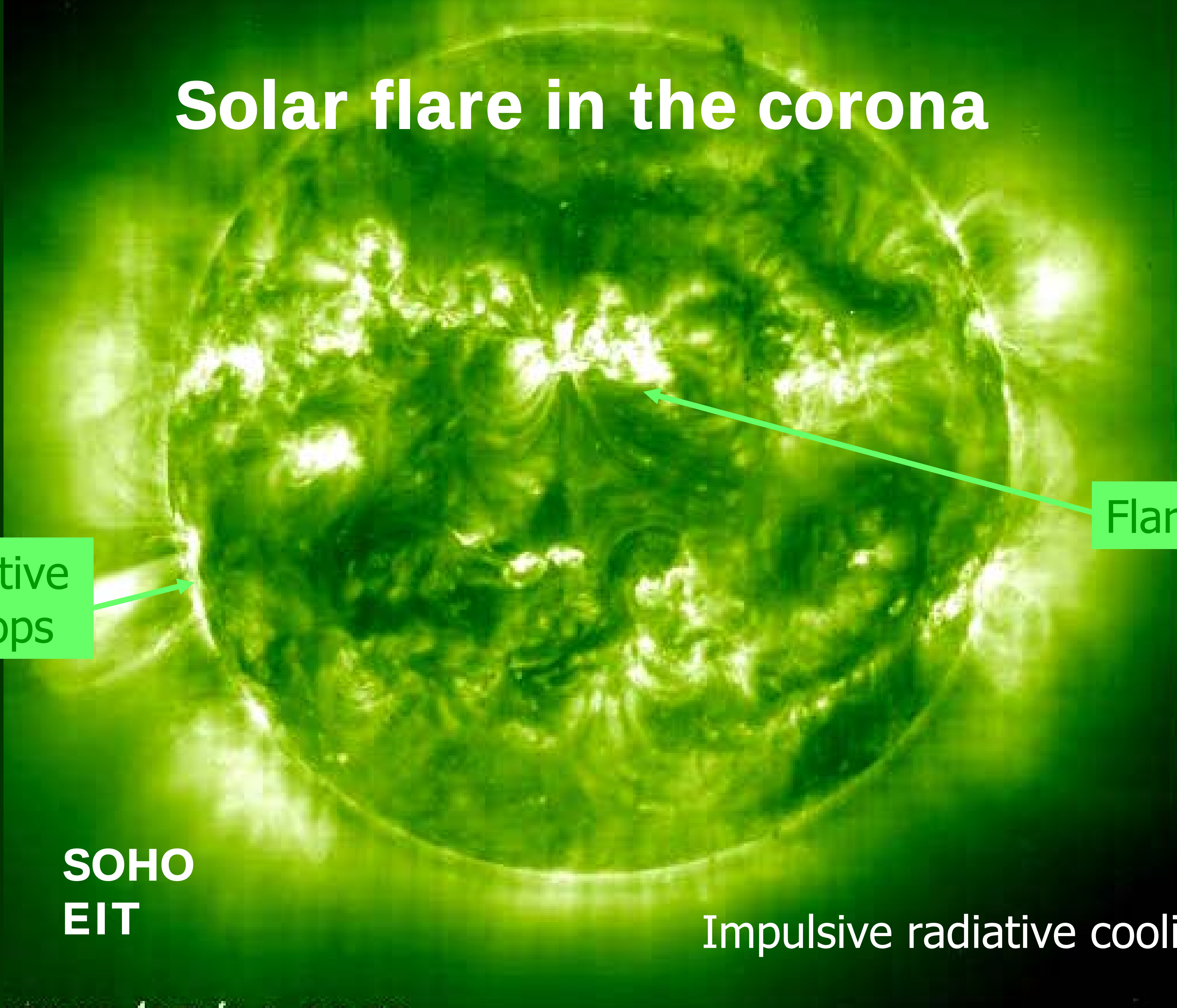
Explosive events (Innes et al., 1997)

- 2 x 10^5 K
- 60 s
- 160 kms^{-1}
- 2 arcsec (1500 km)

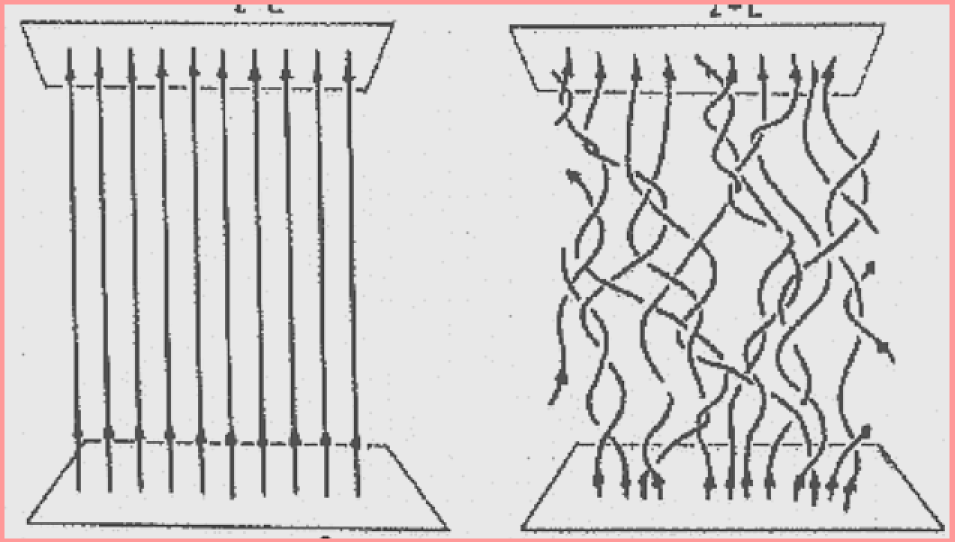
Blinkers (Harrison, 1997)

- 2 x 10^5 K
- 1000 s
- 20 kms^{-1}
- 10 arcsec (7500 km)

Solar flare in the corona



Ubiquitous magnetic reconnection



Parker's (1988) nanoflare concept

Power-law of flare frequency f **against energy** E

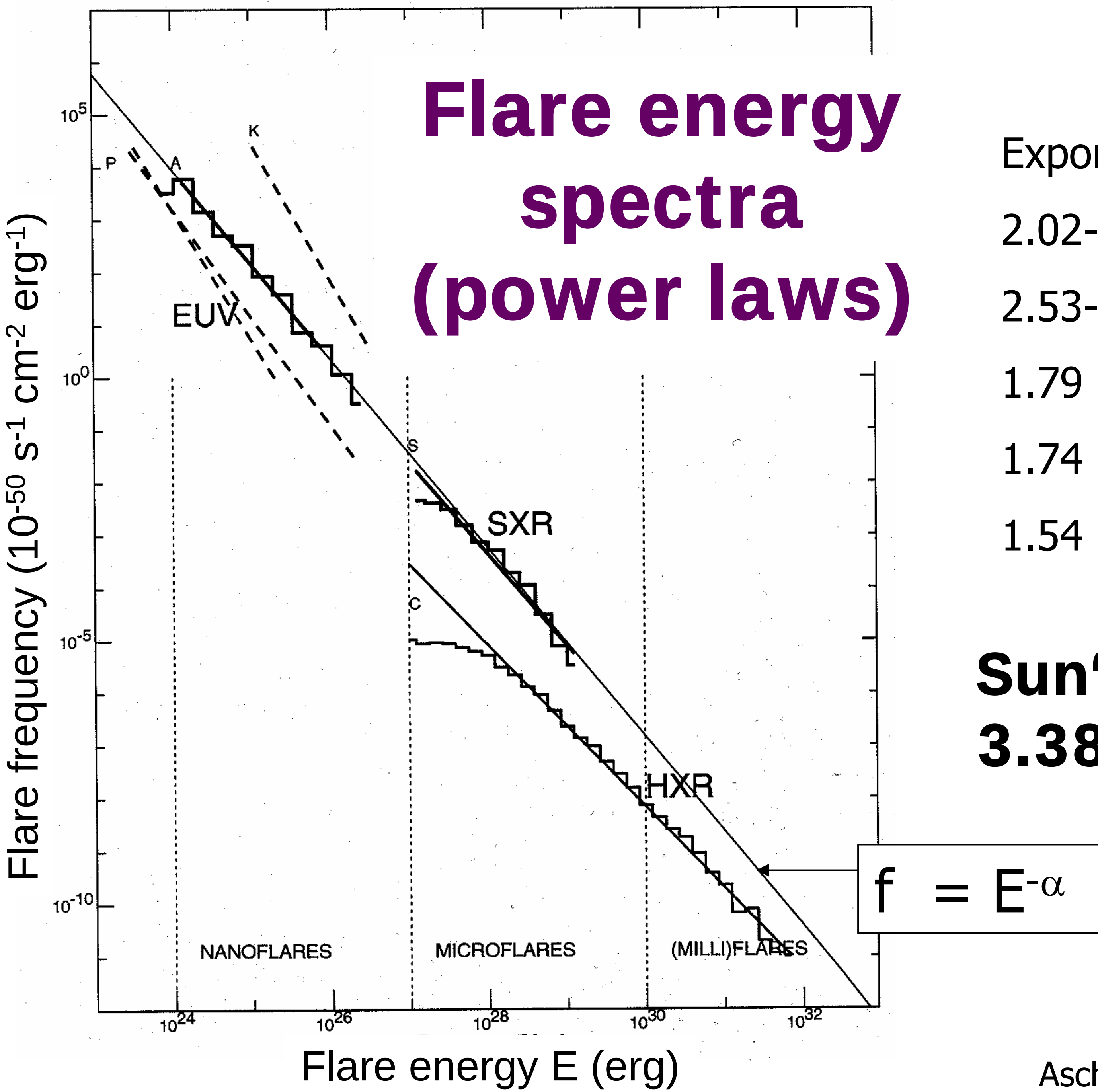
$$f(E) = f_0 E^{-\alpha}$$

Spectral index, α < -2, for nanoflare dominated heating

Self-organised criticality:

- Corona is modeled as an externally driven, dissipative dynamical system.
- Larger catastrophes are triggered by a chain reaction of many smaller events.

Flare energy spectra (power laws)

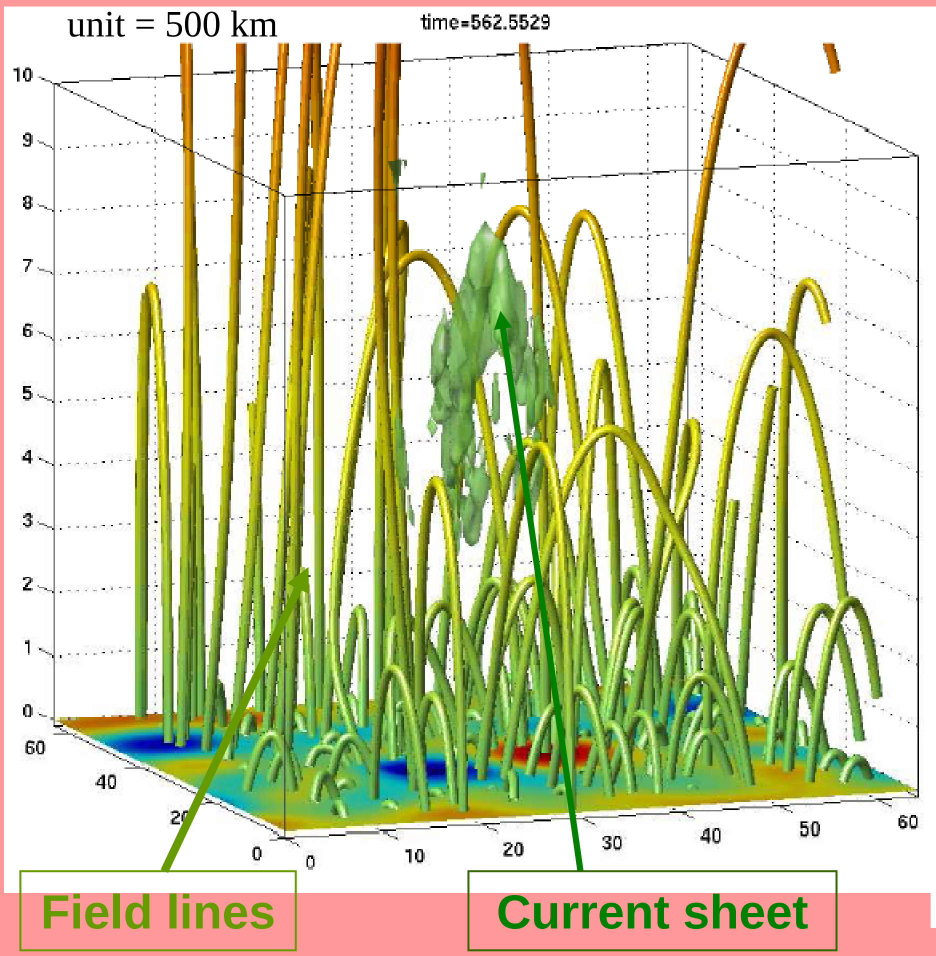


Exponent α	Number
2.02-2.42	4497 (P)
2.53-2.50	11150 (K)
1.79 (0.08)	281 (A)
1.74	291 (S)
1.54	2878 (C)

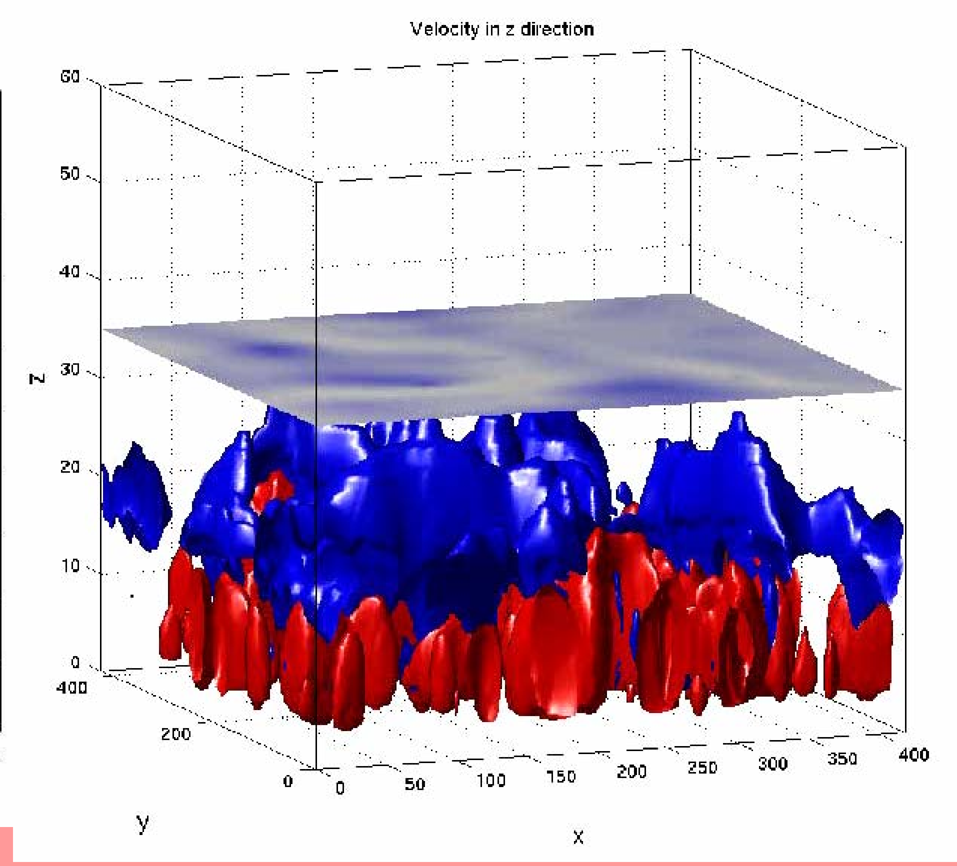
Sun's luminosity $3.38\ 10^{33}$ erg/s

Aschwanden et al., 2000

Reconnection in transition region



Doppler blue and red shift (±10 km/s)



Results from numerical multi-fluid simulation with anomalous resisitivity

Büchner and Nikutowski, 2004, 2005

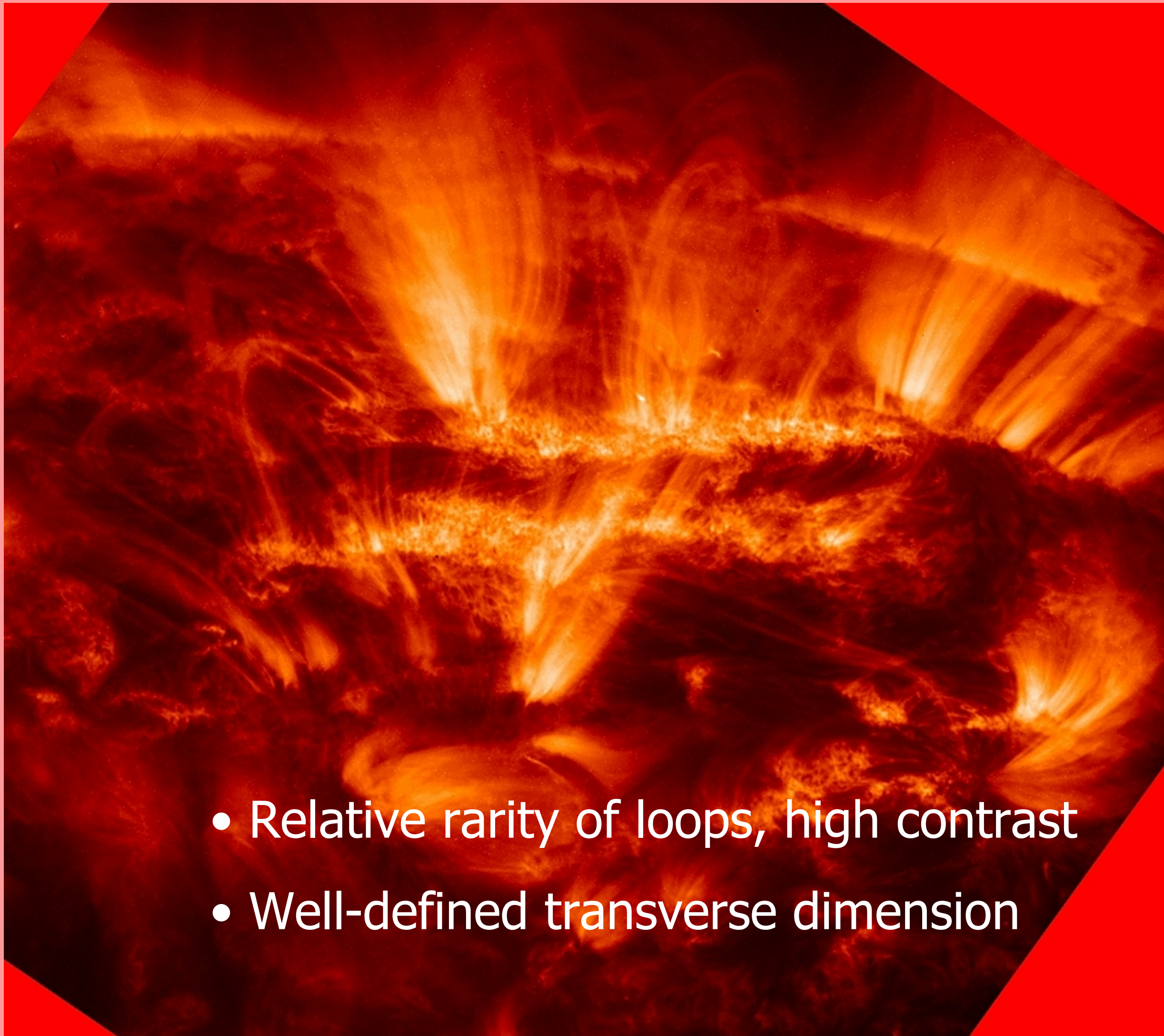
Coronal ultraviolet emission from multiple filamentary loops

1. Filamentary nature of loops is consequence of fine solar surface fields....

2. Transient localised heating with threshold.....

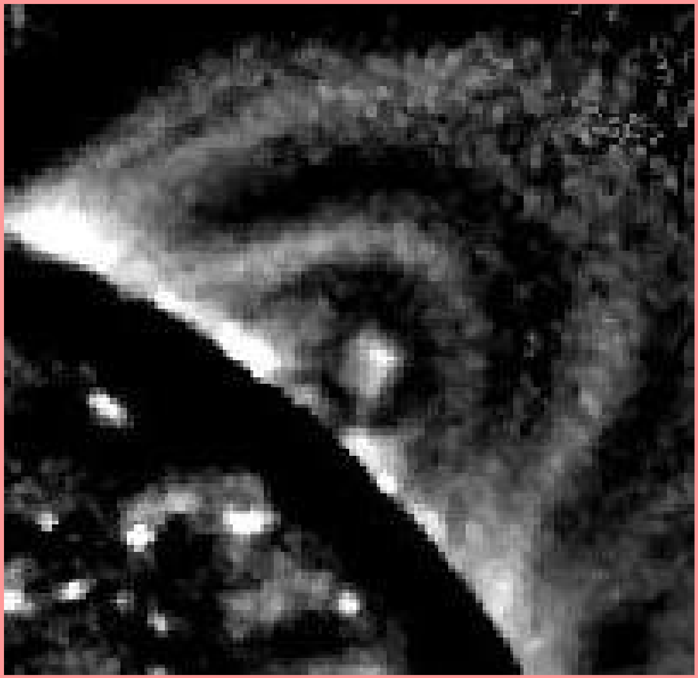
3. Non-classical diffusive perpendicular transport by turbulence too slow....

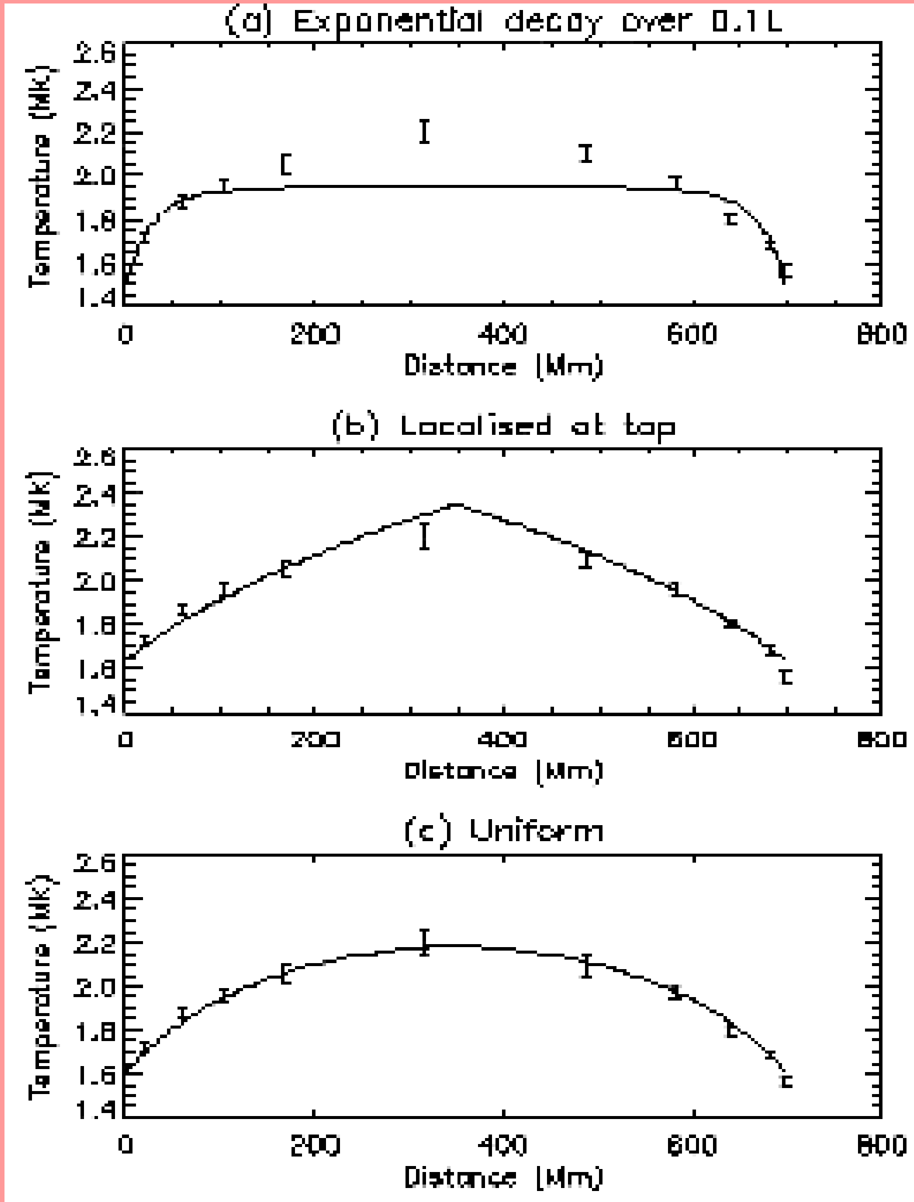
4. Field line stochasticity...



Litwin & Rosner, ApJ **412**, 375, 1993

Measuring thermal structure of loops





- Yohkoh/SXT observations
- Spatially uniform heating

Priest et al., 2000

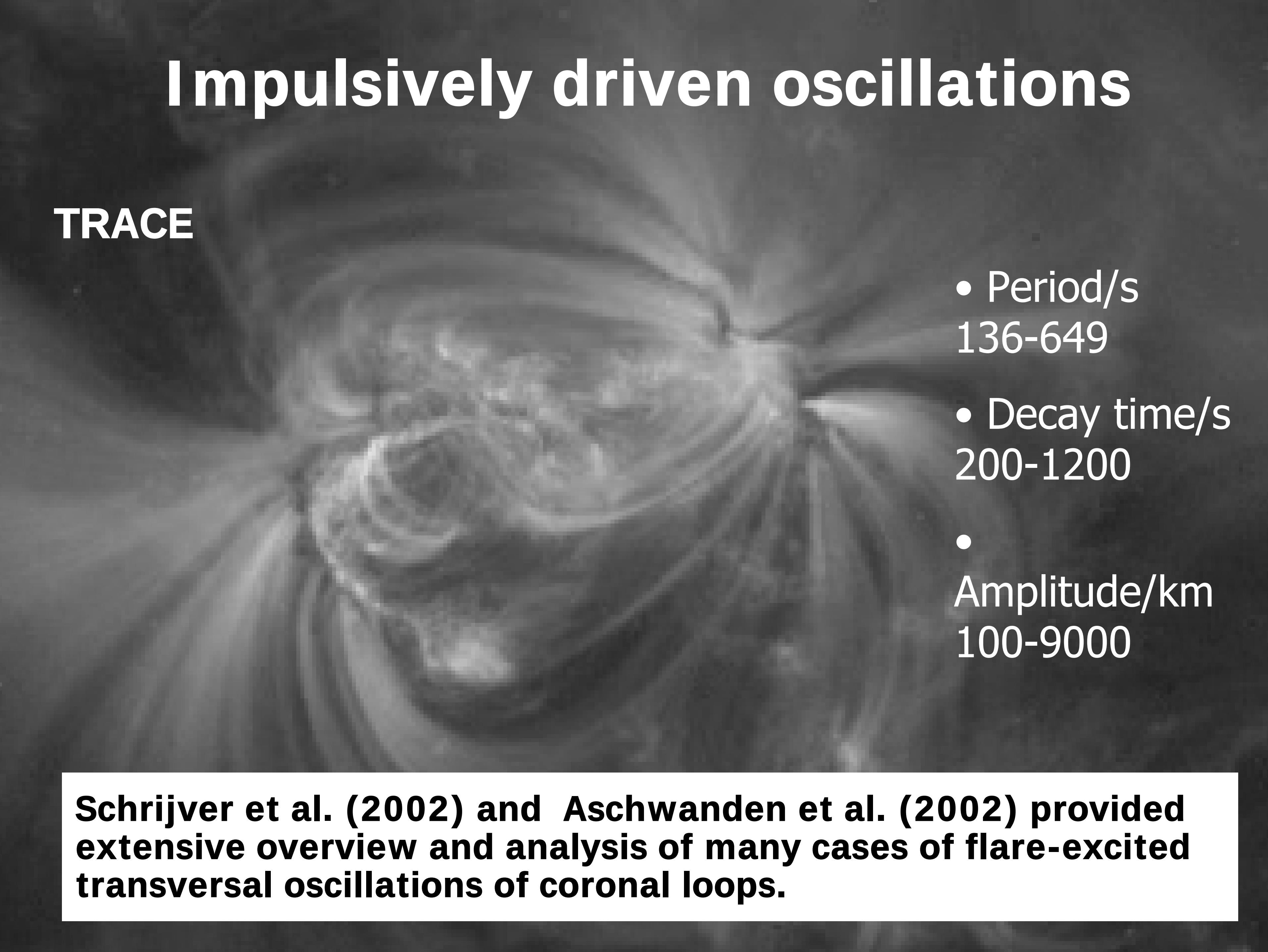
Coronal heating - an unsolved problem

Why?

Incomplete and insufficient diagnostics:

- **Only remote-sensing through photons (X-rays, extreme ultraviolet (EUV), visible, infrared) and electromagnetic waves (radio, plasma), and corpuscular radiation (solar wind, energetic particles)**
- **No coronal in-situ measurements, such as possible in other solar system plasmas (Earth‘s magnetosphere, solar wind,.......)**

Impulsively driven oscillations



TRACE

- Period/s 136-649
- Decay time/s 200-1200
- Amplitude/km 100-9000

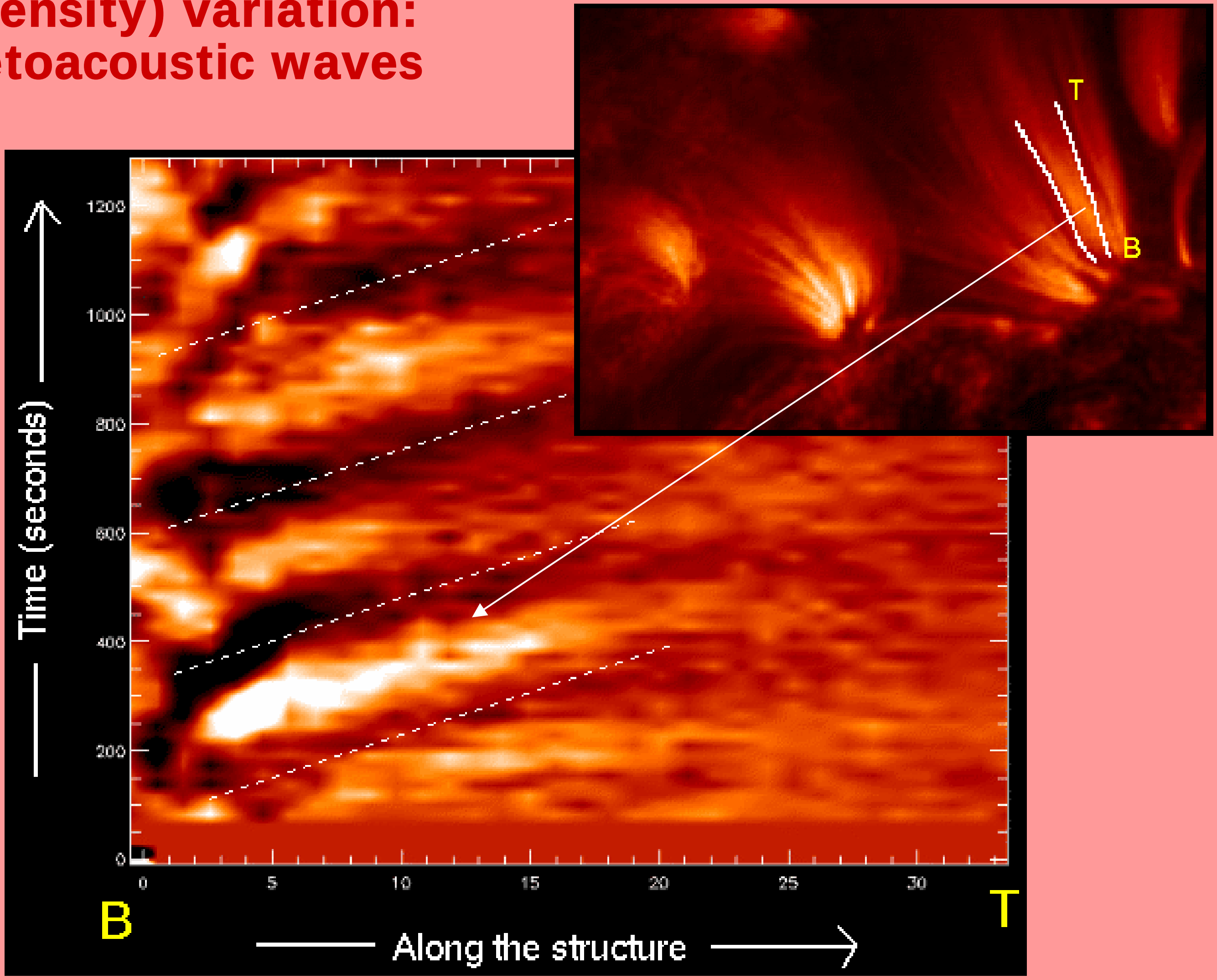
Schrijver et al. (2002) and Aschwanden et al. (2002) provided extensive overview and analysis of many cases of flare-excited transversal oscillations of coronal loops.

Detection of longitudinal waves

Intensity (density) variation:
Slow magnetoacoustic waves

TRACE

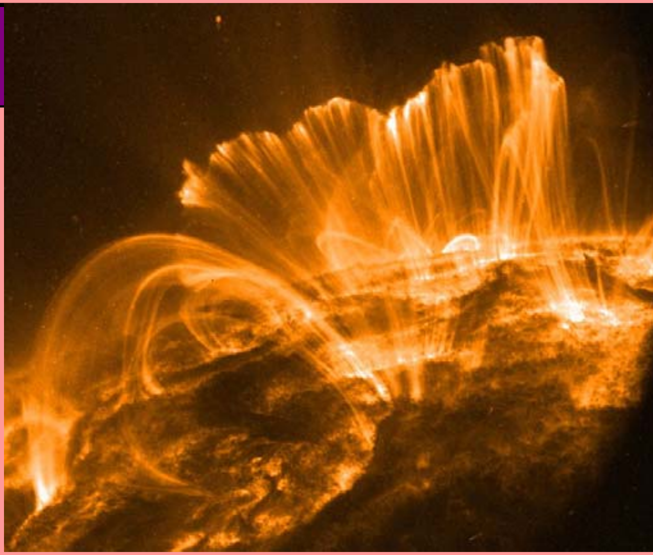
Loop images in Fe 171 Å at 15 s cadence



De Moortel et al., 2000

Loop oscillation properties

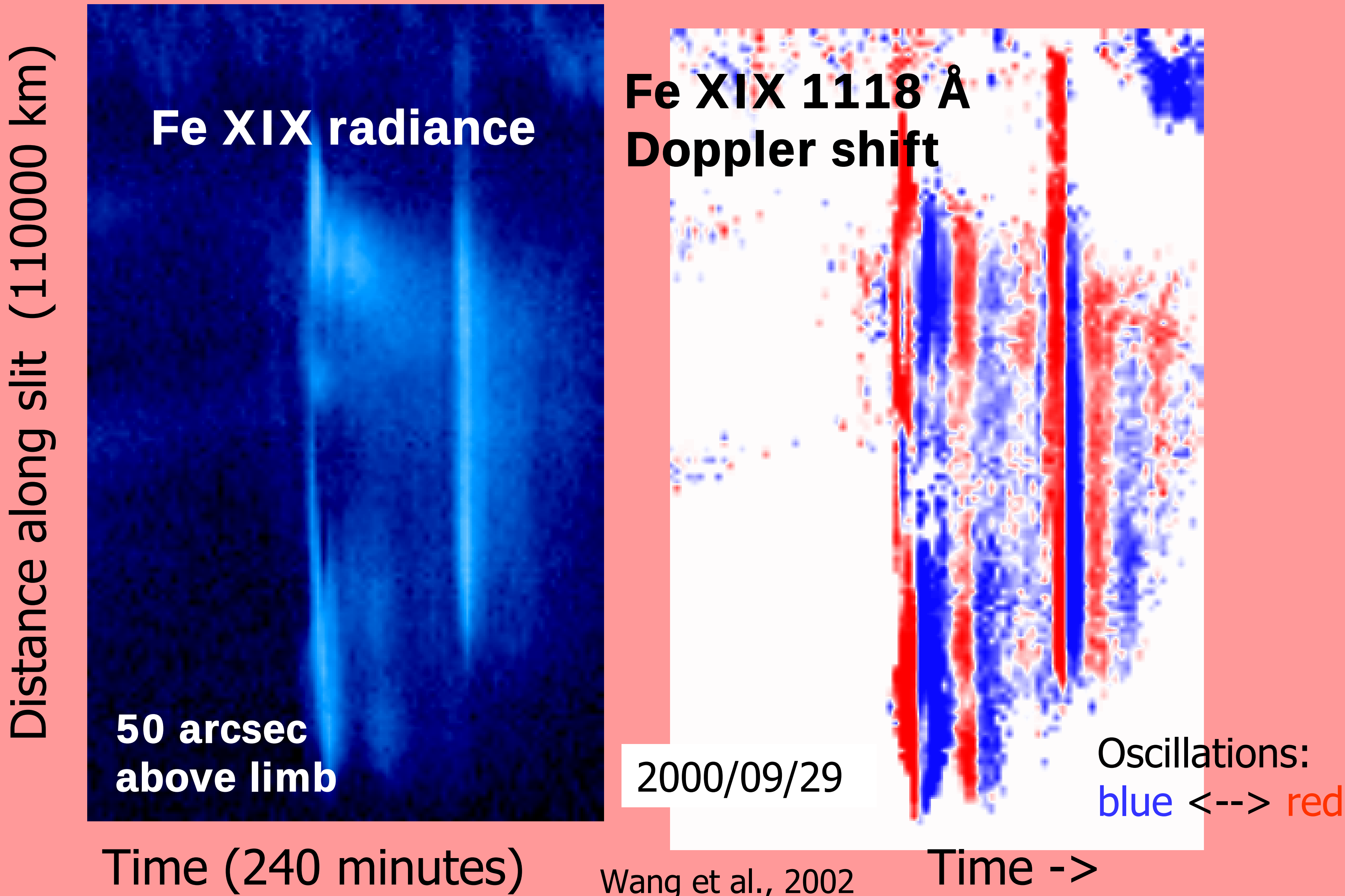
Parameter	Range
Footpoint length	10.2 - 49.4 Mm
Footpoint width	3.9 - 14.1 Mm
Transit period	1.3 - 6.3 s
Propagation speed	65 - 205 km s^{-1}
Relative amplitude	0.7 - 14.6 %
Damping length	2.9 - 18.9 Mm
Energy flux	195 - 705 mW m^{-2}



De Moortel, Ireland and Walsh, 2002

Statistical overview of the ranges of the physical properties of 38 longitudinal oscillations detected at the base of large coronal loops (1 R_S = 700 Mm).

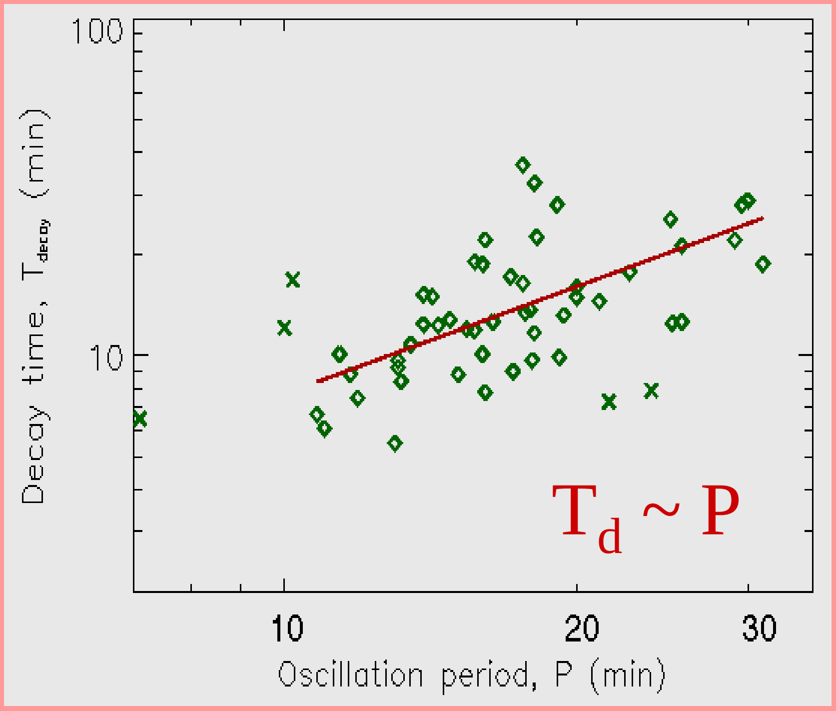
Loop oscillations in solar corona



Damping of hot-loop oscillations

SUMER: 49 cases in 27 events

$$T_{decay} = 0.68^{+0.46}_{-0.27} P^{1.06\pm0.18}$$

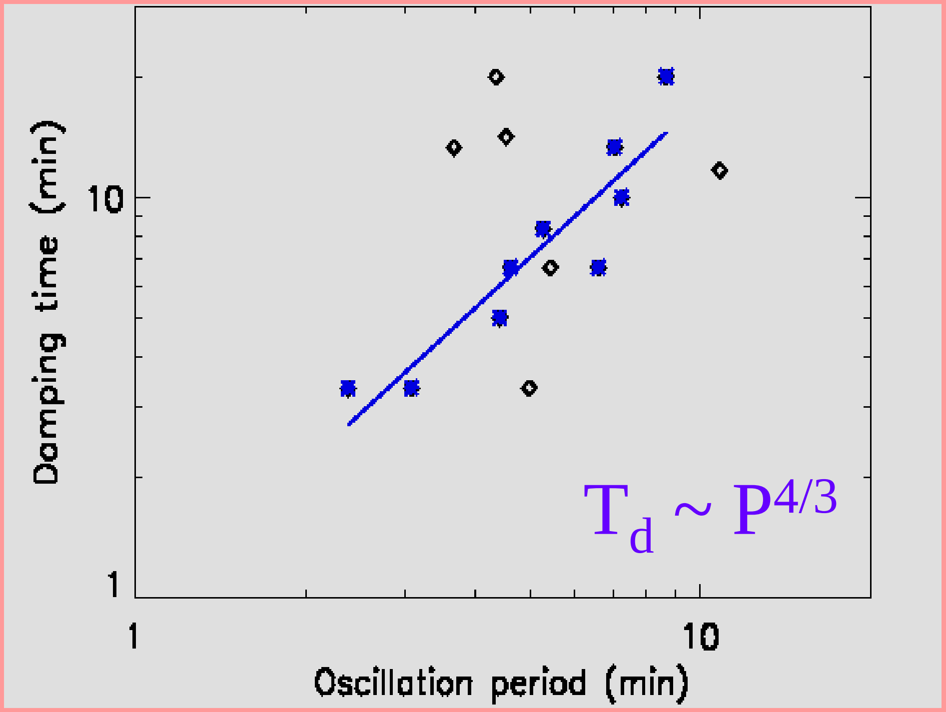


In agreement with higher dissipation rate, due to **thermal conduction** and **viscosity** when T is higher.

Wang et al., 2003

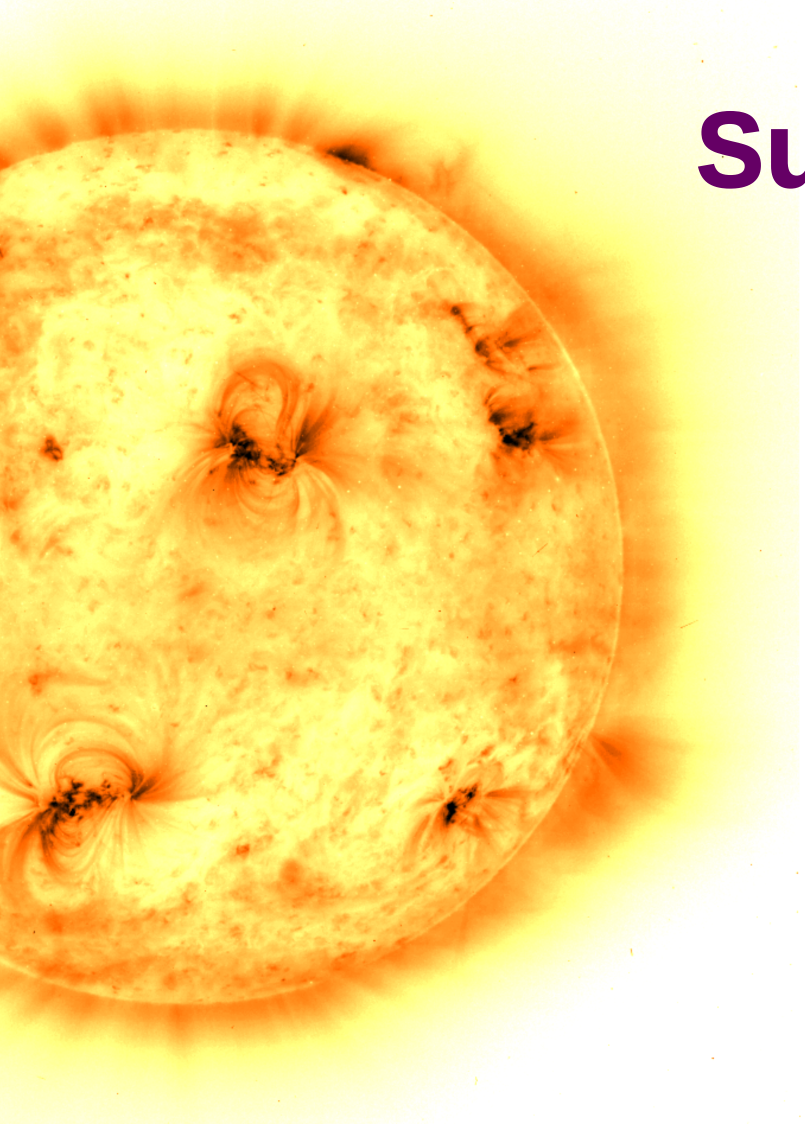
TRACE: 11 cases

$$T_{decay} = 0.9\ P^{1.30\pm0.21}$$



In agreement with dissipation by **phase mixing** for kink-mode oscillations.

Ofman & Aschwanden, 2002



Summary

- Corona, a restless, complex non-uniform plasma and radiation environment dominated by the solar magnetic field
- Evidence for quasi-periodic stiff oscillations and waves through the entire solar atmosphere and in loops
- Many small-scale brightenings in a wide range of wavelengths and with a power-law distribution in energy

Microscopic heating mechanism is unknown!