Convective Instability and the Formation of Solar Magnetic Flux Tubes

-observational evidence for convective collapse-

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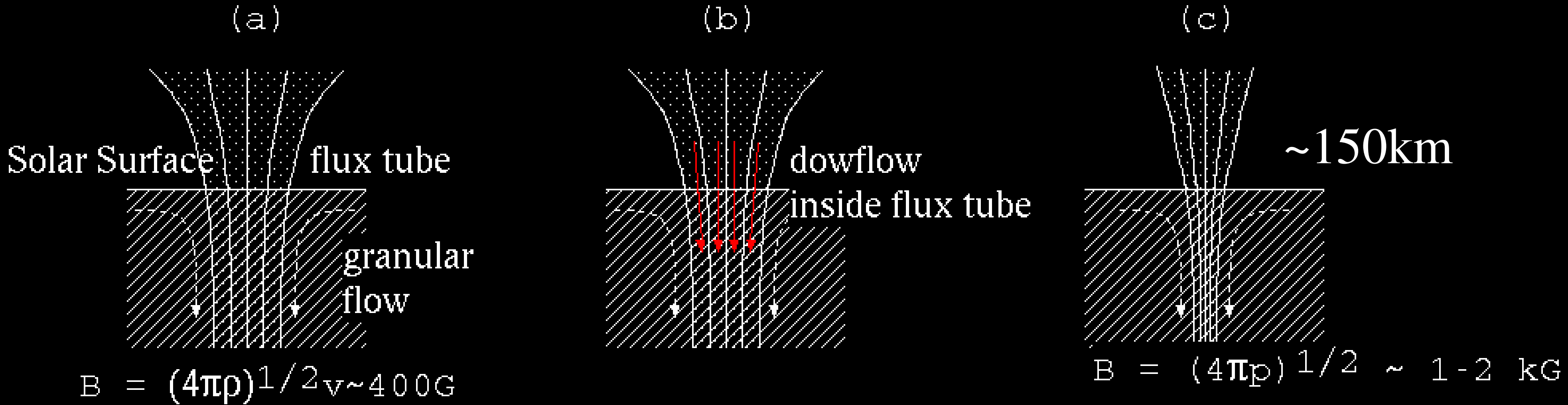
Outline of the talk

- Qualitative analysis
  - Convective collapse
  - Clear observational evidence (just one case)
- Quantitative understanding of convective collapse
  - Convective stability of thin flux tube
  - Comparison between observed evolution and the model
- Summary

Convective Collapse

A model to explain the formation of kilo-gauss field flux tube on the Sun
Parker (1978); Webb & Roberts (1978); Spruit & Zweibel (1979)



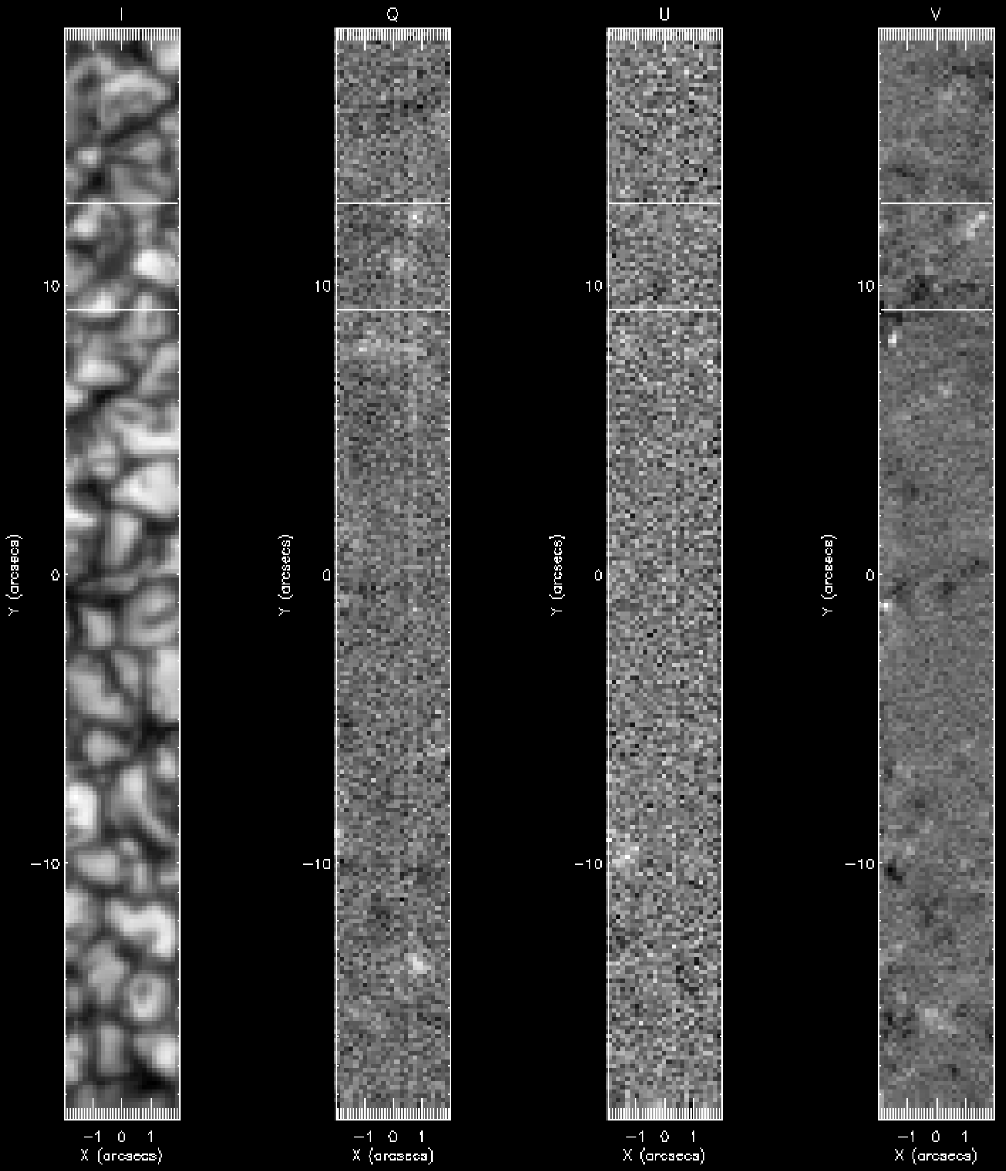
a) Magnetic Fields are swept into the inter granular lanes; flux expulsion. The field strength archived in this process is ~ 400 G. (Equipartition field)
b) Convective instability inside the flux tube lead to the down flow.
c) The evacuated flux tube shrinks to balance the magnetic pressure with the surrounding gas pressure, the resultant field strength is kilo gauss.

SEEING PREVENTED TESTING BY GROUND BASED OBAERVATIONS

So, here come the Hinode

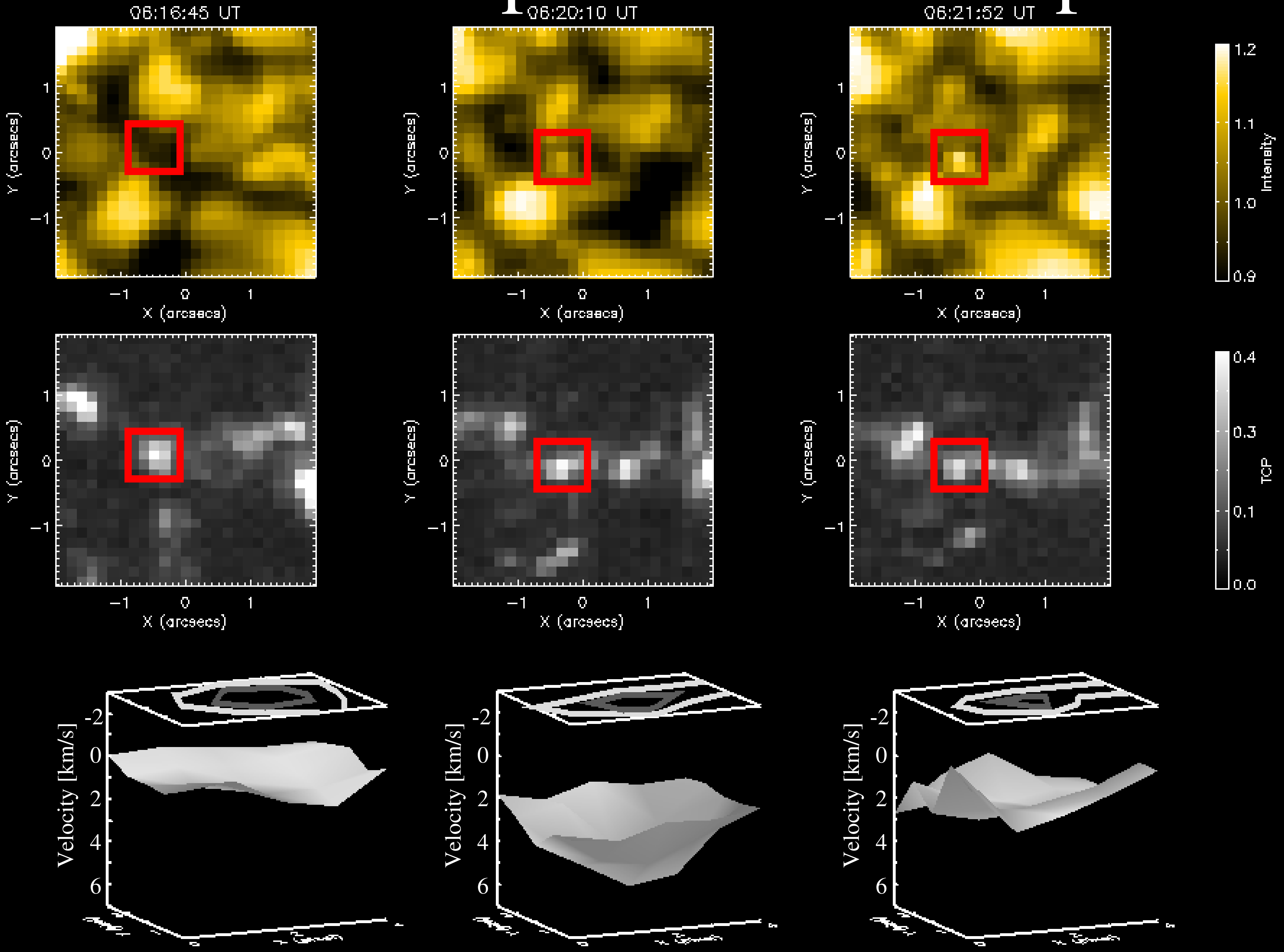
Observation and Analysis

6-Feb2007 06:08 – 07:09 at the disk center



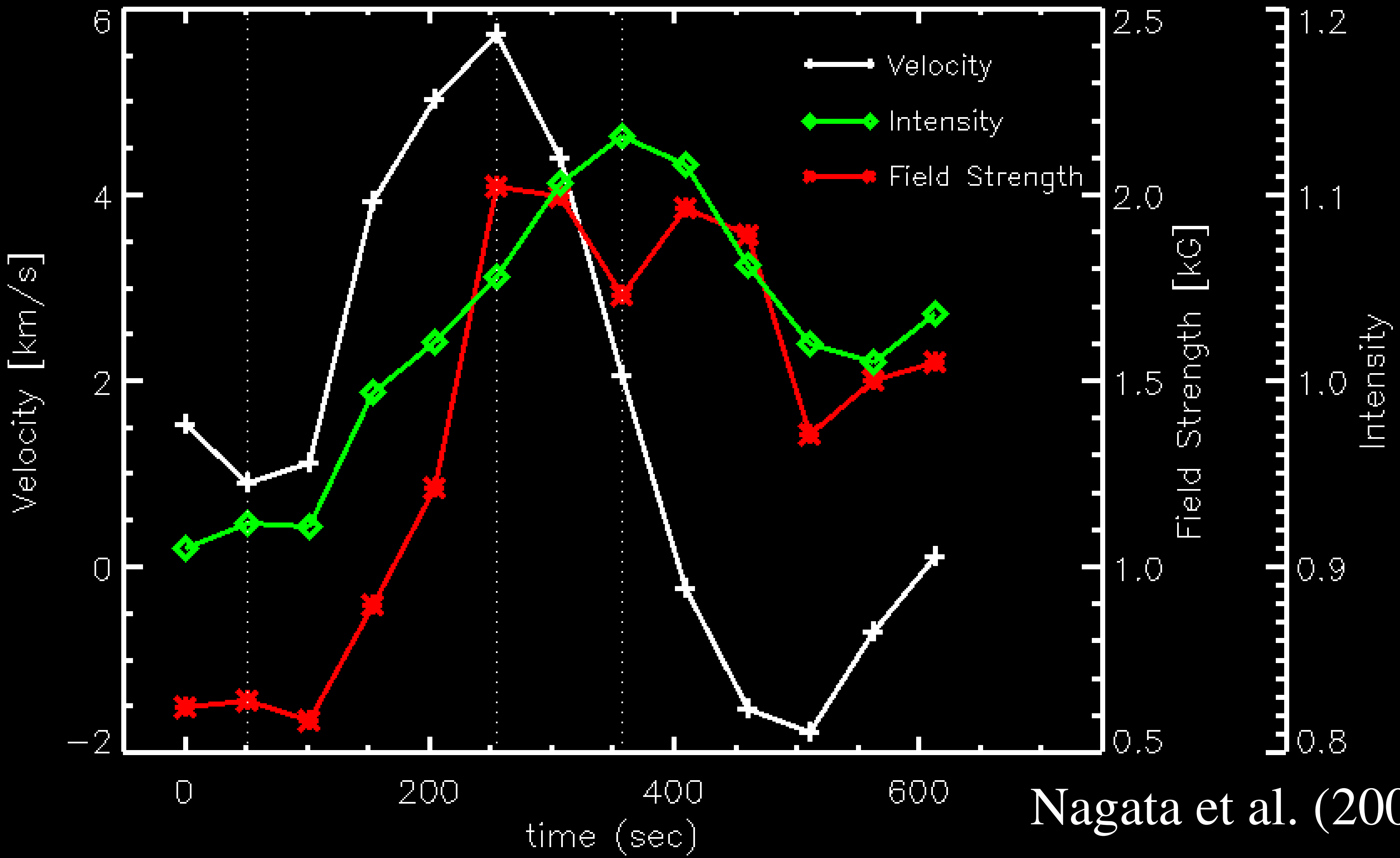
- SP dynamics mode (4”x40”, 50sec cadence)
- No significant signal larger than polarimetric SN ratio observed in Q and U profiles (>3σ).
- I and V profiles were analyzed.
  - V-profile zero-Cross velocity
  - I-profile continuum intensity
- ME Inversion for field strength
- NO FG observations

The most prominent example



Nagata et al. (2008)

The most prominent example



Nagata et al. (2008)

The field strength intensification along with the growing downflow is *qualitatively* consistent with the theoretical prediction.

Quantitative understanding

- Time evolution of asymmetric profiles
  - ***Flux tube stratification along the line of sight*** can be examined from the ***sophisticated inversion method***
- Statistical analysis with many examples
  - ***Compare the observations with convective instability of 1D flux tube model***

1D flux tube model equations

Equations

$$\frac{\partial}{\partial t}\left(\frac{\rho}{B}\right)+\frac{\partial}{\partial z}\left(\frac{\rho v}{B}\right)=0\cdots(1)$$

$$B(z)A(z)=const,\ \frac{\partial}{\partial t}(\rho A)+\frac{\partial}{\partial z}(\rho A v)=0$$

$$\rho\left(\frac{\partial}{\partial t}v+v\frac{\partial}{\partial z}v\right)=-\frac{\partial P}{\partial z}-\rho g\cdots(2)$$

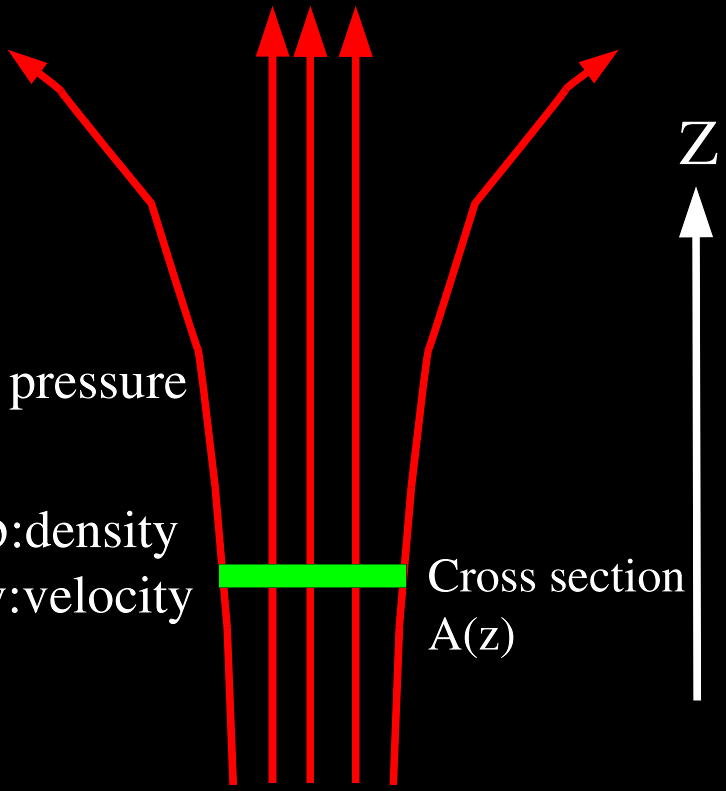
$$P+\frac{B^2}{8\pi}=P_e\cdots(3)$$

$$\frac{\partial P}{\partial t}+v\frac{\partial P}{\partial z}=\frac{\gamma P}{\rho}\left(\frac{\partial \rho}{\partial t}+v\frac{\partial \rho}{\partial z}\right)\cdots(4)$$

(1) continuity
(2) Equation of motion (z-direction)
(3) Equation of motion (pressure balance)
(4) Energy equation (adiabatic)

Thin Flux Tube model

Robers & Webb (1978)



P_e:gass pressure outside

ρ:density
v:velocity

Cross section
A(z)

B:magnetic field strength
P:gass pressure inside tube

Linear analysis results: stability depends on β

Webb & Roberts(1978) shows that the perturbation satisfies the Sturm-Liouville equation (eigenvalue problem)

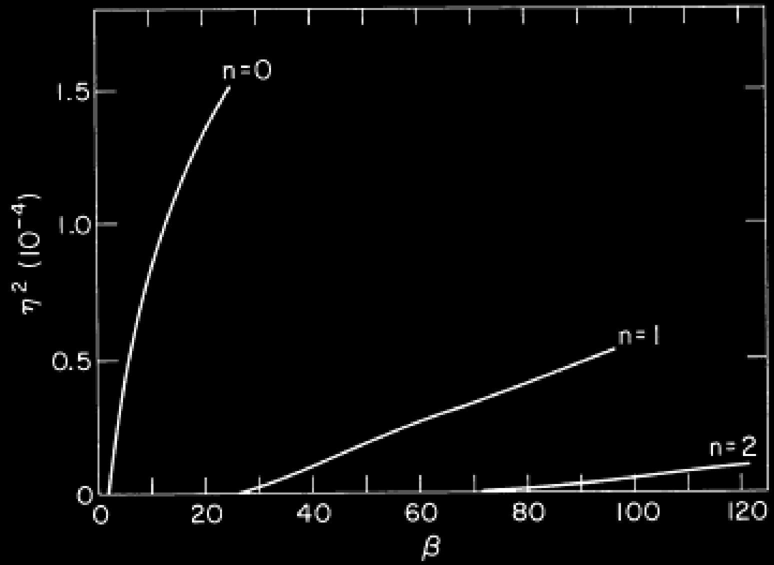
Linearized equation of (1)-(4)

$$v = v(z) e^{i\omega t} \qquad \frac{d^2 v}{dz^2} - \frac{1}{\Lambda_i}\frac{dv}{dz} + \left[\frac{\omega^2 - N_i^2}{c_T^2} + \left(1 - \frac{\gamma}{2}\right)\frac{N_i^2}{c_{si}^2}\right] v = 0$$

Spruit & Zweibel (1979) numerical solved, and found critical value of the plasma beta; convectively stable if $\beta < \beta_c$ ($\beta_c = 1.83$)

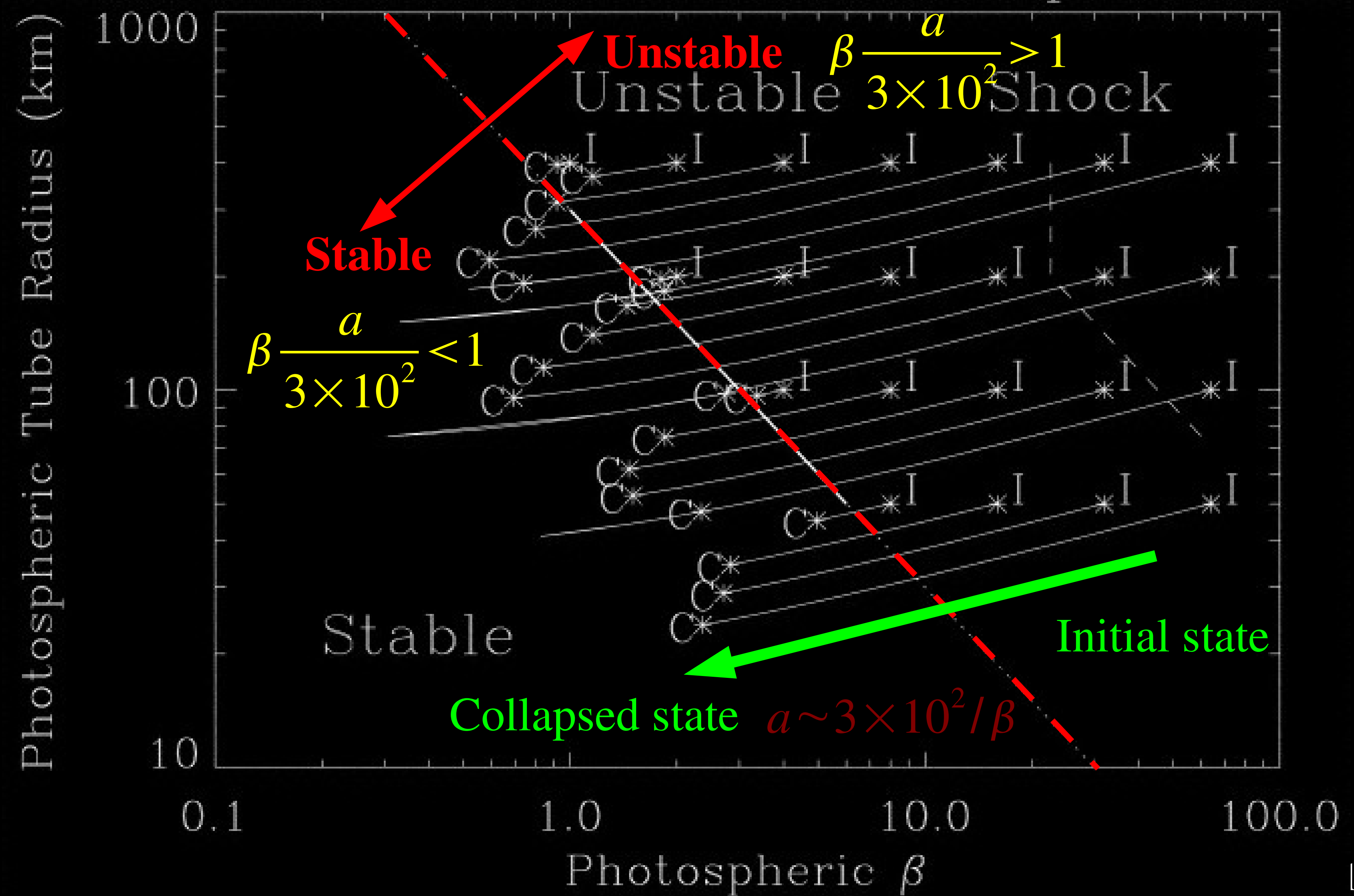
Hasan (1986)
improved energy equation using Newton's law of cooling; β_c depends on the tube radius

Growth rate (iw) dependence on β



Nonlinear analysis result

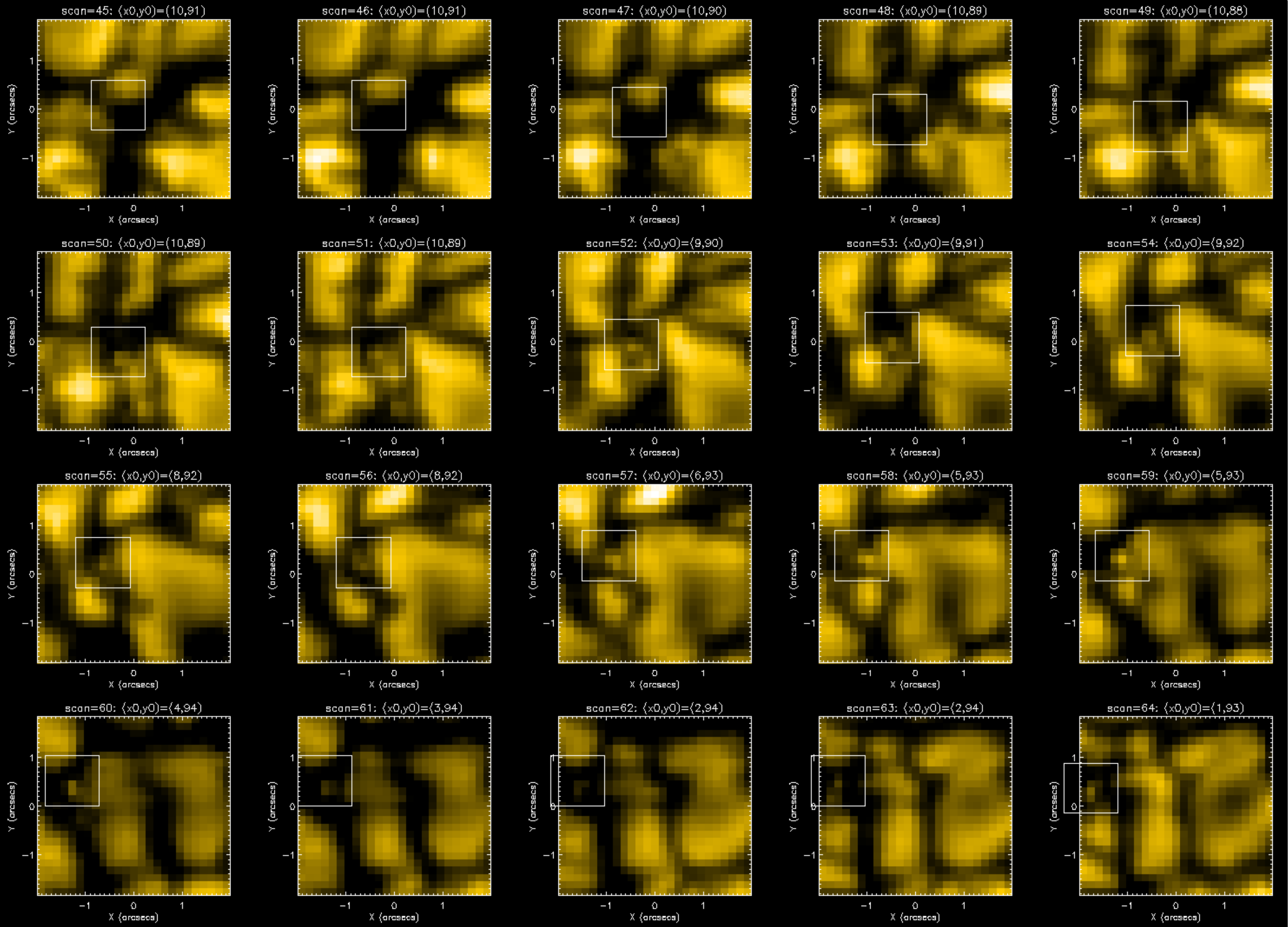
1D flux tube evolution by Takeuchi (1999) revised the β_c expression



We use the diagram for this study

More examples from 6-Feb-2007 data

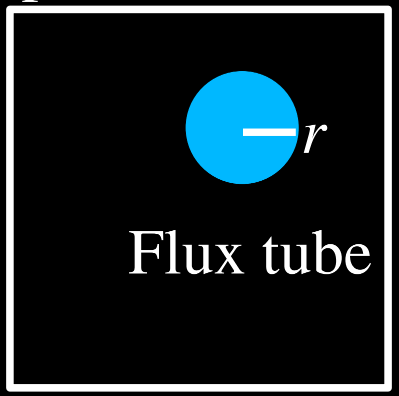
- Identification of events by visual inspection
  - 34 downflow events are identified in the Vzc map
  - 8 of 34 are accompanied with growing continuum bright point are analyzed, including the most prominent one


scan=45: (x0,y0)=(10,91)
scan=46: (x0,y0)=(10,91)
scan=47: (x0,y0)=(10,90)
scan=48: (x0,y0)=(10,89)
scan=49: (x0,y0)=(10,88)
scan=50: (x0,y0)=(10,89)
scan=51: (x0,y0)=(10,89)
scan=52: (x0,y0)=(9,90)
scan=53: (x0,y0)=(9,91)
scan=54: (x0,y0)=(9,92)
scan=55: (x0,y0)=(8,92)
scan=56: (x0,y0)=(8,92)
scan=57: (x0,y0)=(6,93)
scan=58: (x0,y0)=(5,93)
scan=59: (x0,y0)=(5,93)
scan=60: (x0,y0)=(4,94)
scan=61: (x0,y0)=(3,94)
scan=62: (x0,y0)=(2,94)
scan=63: (x0,y0)=(2,94)
scan=64: (x0,y0)=(1,93)
Y (arcsecs)
X (arcsecs)
1
0
−1

Estimation of flux tube radius and plasma β

Flux tube radius:

1 pixel area S



Filling factor definition

$$f = \frac{\pi r^2}{S}$$

Flux tube radius

$$\Rightarrow \quad r = \sqrt{\frac{\pi}{f\,S}}$$

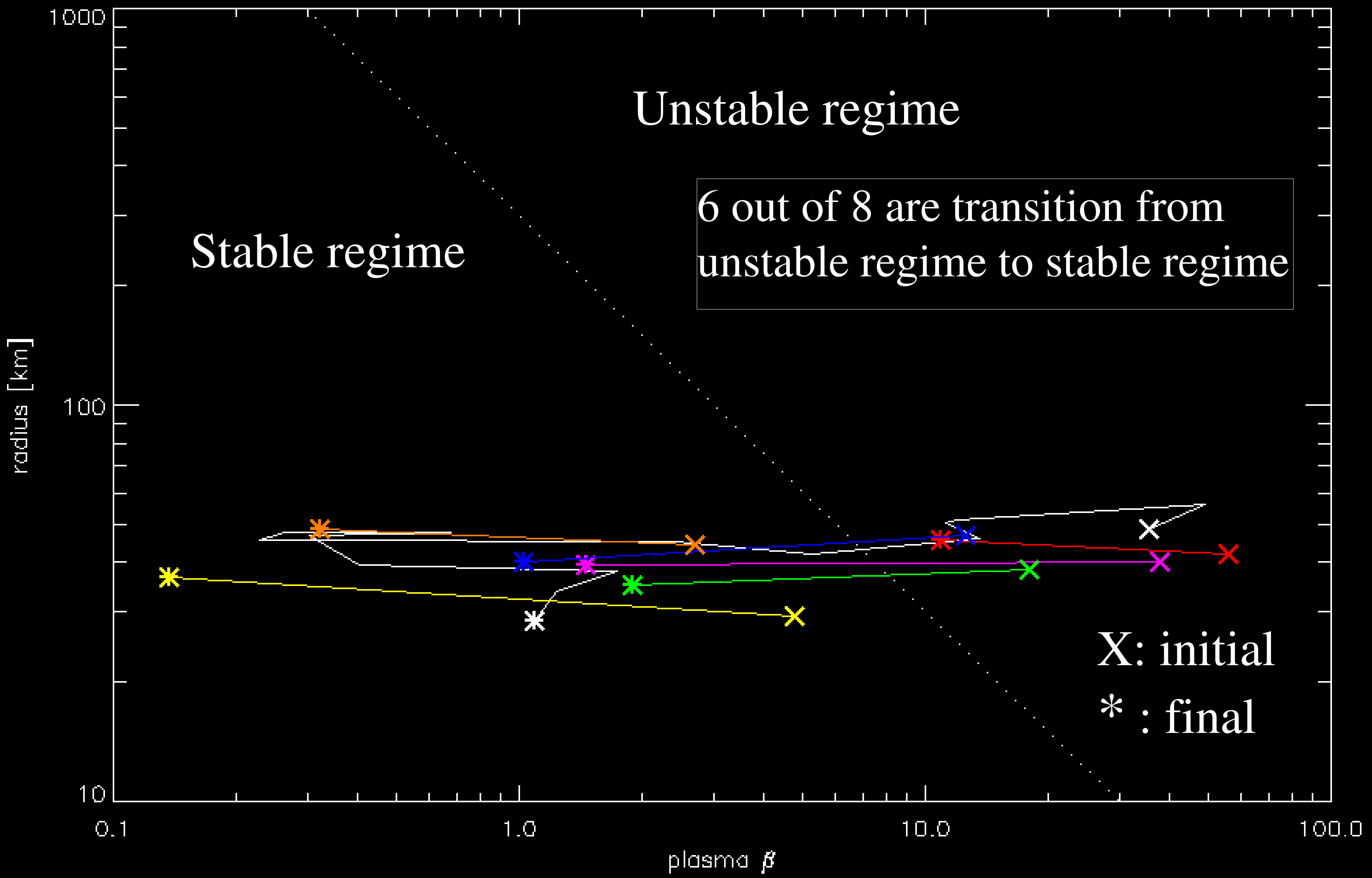
The effective SOT/SP spatial resolution 0.3” => ~220 km (Lites at al. 2008)
filling factor derived from the ME inversion is used

Plasma β:

$$P = P_e - \frac{B^2}{8\pi}, \qquad \beta = \frac{P_e}{\left(\frac{B^2}{8\pi}\right)} - 1, \qquad P_e = 2 \times 10^5$$

Pressure at the formation height ~ 100 km; VAL, Bellot Rubiot (2000)

Evolution curve on β-a diagram



6 out of 8 are transition from unstable regime to stable regime

Summary of 8 BPs

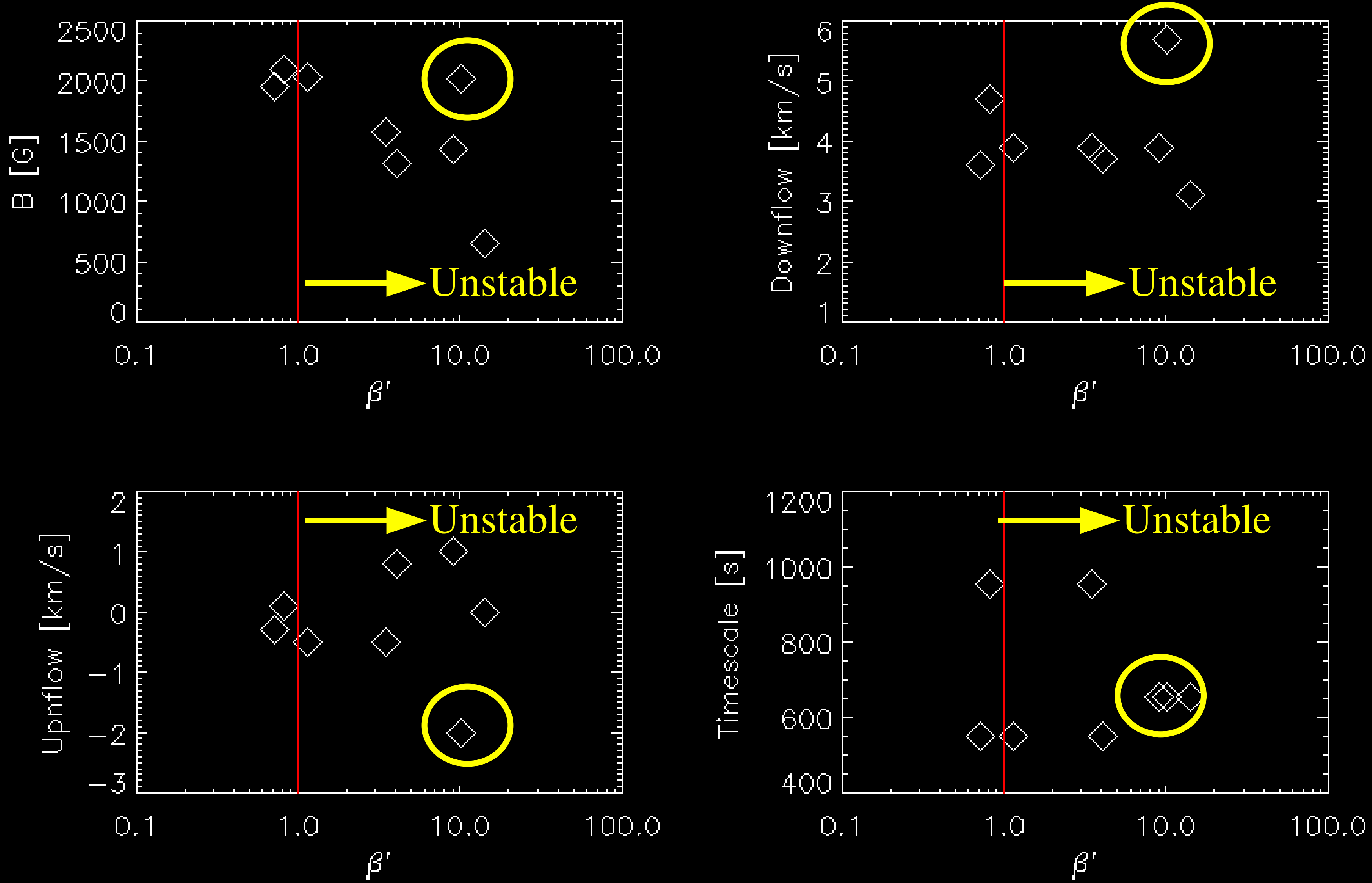
BP	Initial		Collapsed		Max Vzc [km/s]		Time scale [s]
	f	B [G]	f	B [G]	Down	Up	
1	0.41	967	0.31	2037	3.9	-0.5	552
15	0.34	359	0.33	1428	3.9	1.0	653
21	0.18	934	0.29	2102	4.7	0.1	954
24	0.38	297	0.44	649	3.1	0.0	653
30	0.31	513	0.26	1314	3.7	0.8	552
32	0.46	608	0.34	1574	3.9	-0.5	954
33	0.41	1162	0.50	1949	3.6	-0.3	552
34	0.50	371	0.44	2022	5.7	-2.0	603

$$\beta' = \beta \frac{a}{3\times 10^2}$$

Stability depends on β'; correlation between β' and other parameters

Relation between initial β' and collapsed state

Relation between collapsed state parameters and β' is not clear



Summary

- A kilo-gauss field strength flux tube formation accompanied with downflow and bright point formation is qualitatively consistent with convective collapse model.
- Comparison of observations with 1D model
  - Evolution of a-β diagram of 8 examples agree with transition from unstable to stable regime.
  - Instability dependence on initial β is not clear [uncertainty of inversion? data selection? model? Need careful analysis with more examples]
  - Sophisticated inversion