Radio and X-Ray Emission from Stellar Coronae

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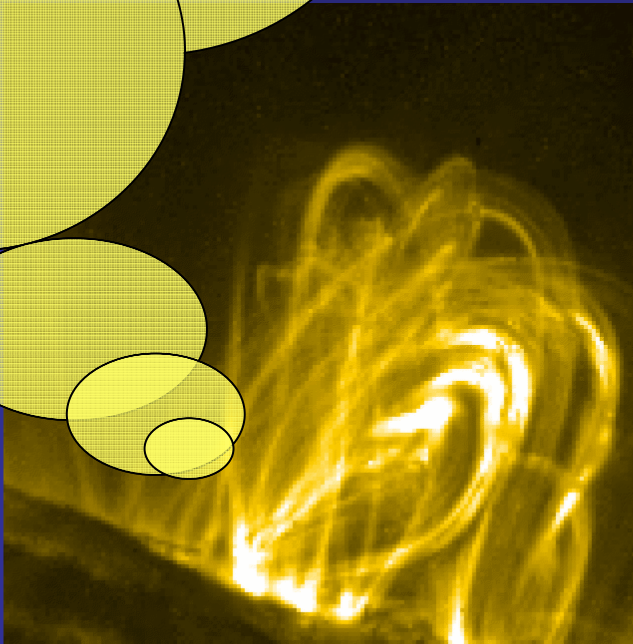
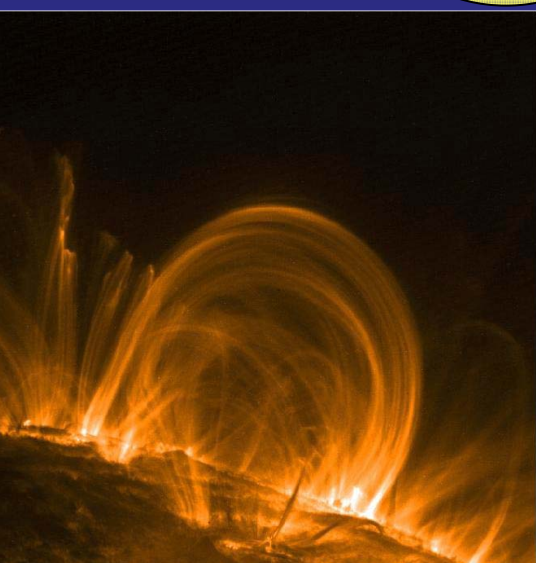
Bonn, 12 November 2006

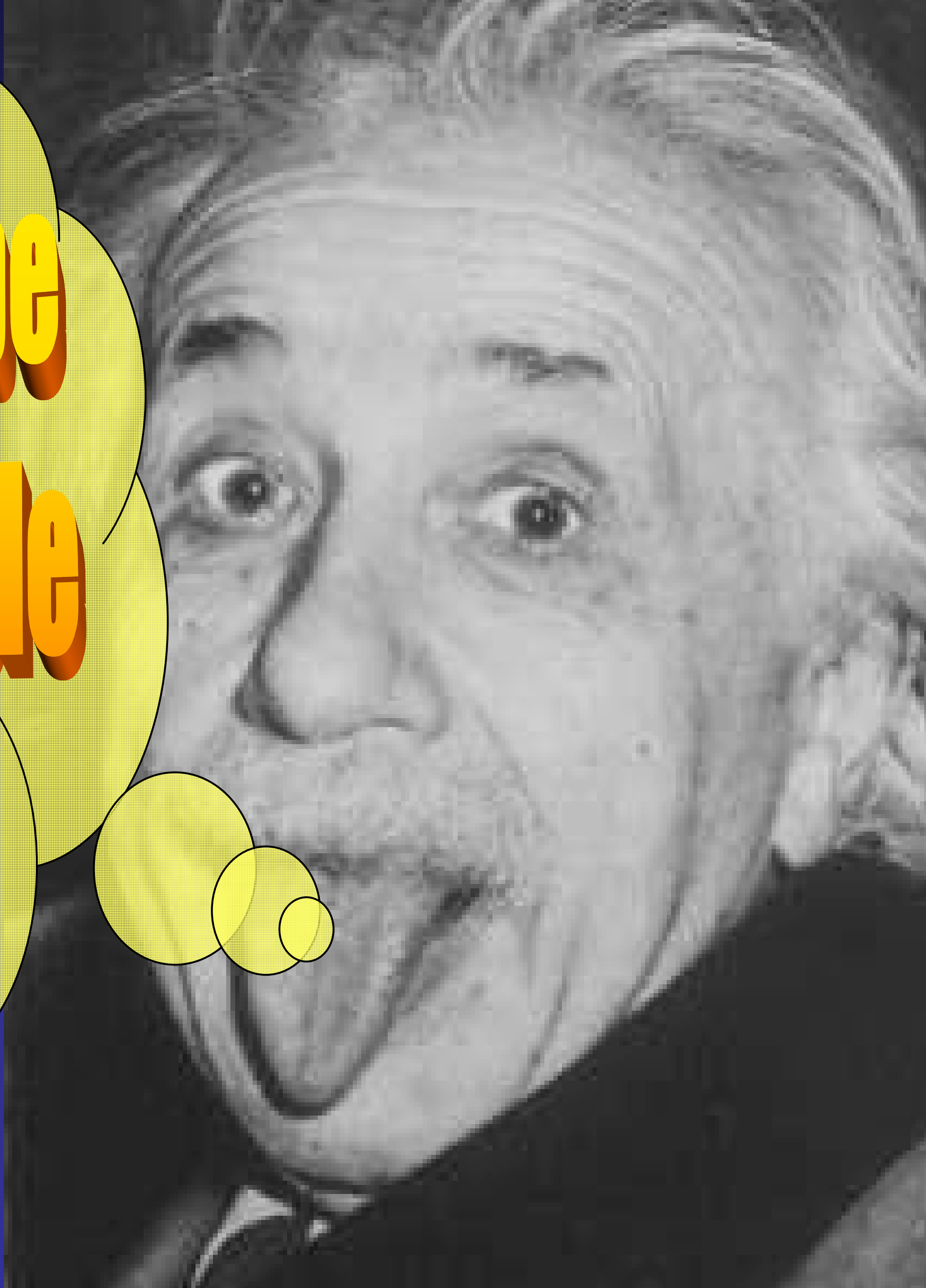
Coronae are complicated!



Pessimist!!



Everything should be as simple as possible but no simpler...



Outline:

Motto: Scepticism is useful

- Coronal structure

- Flares: Bringing mass into the corona

- How are stellar coronae energized?

- Exotic coronae? "Dark coronae"?

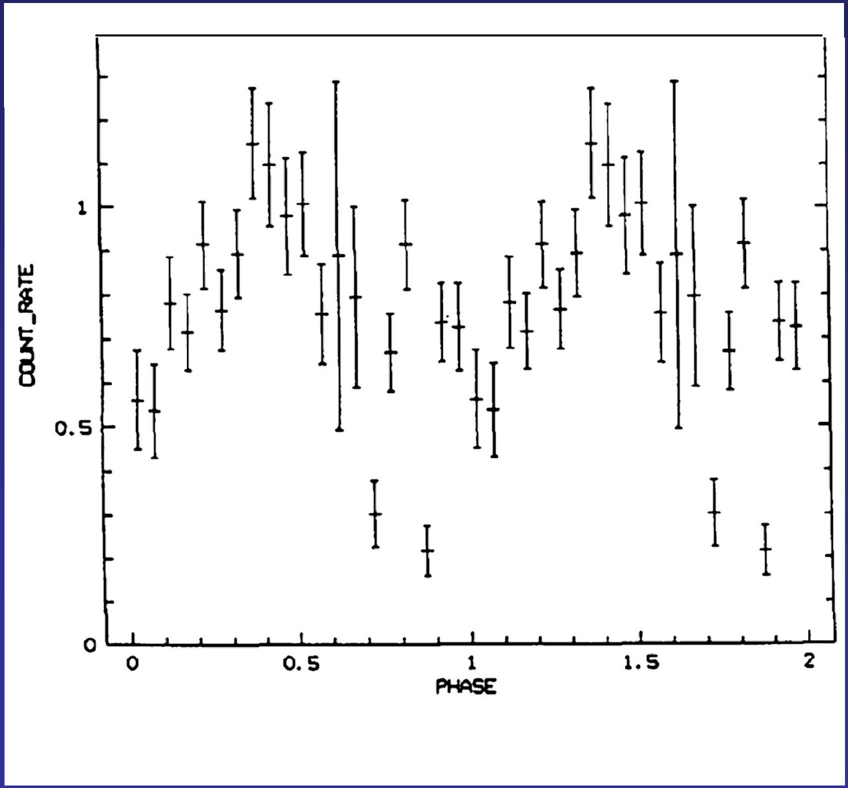
Conclusions: Where are the gaps in our understanding?

How are Coronae Structured?

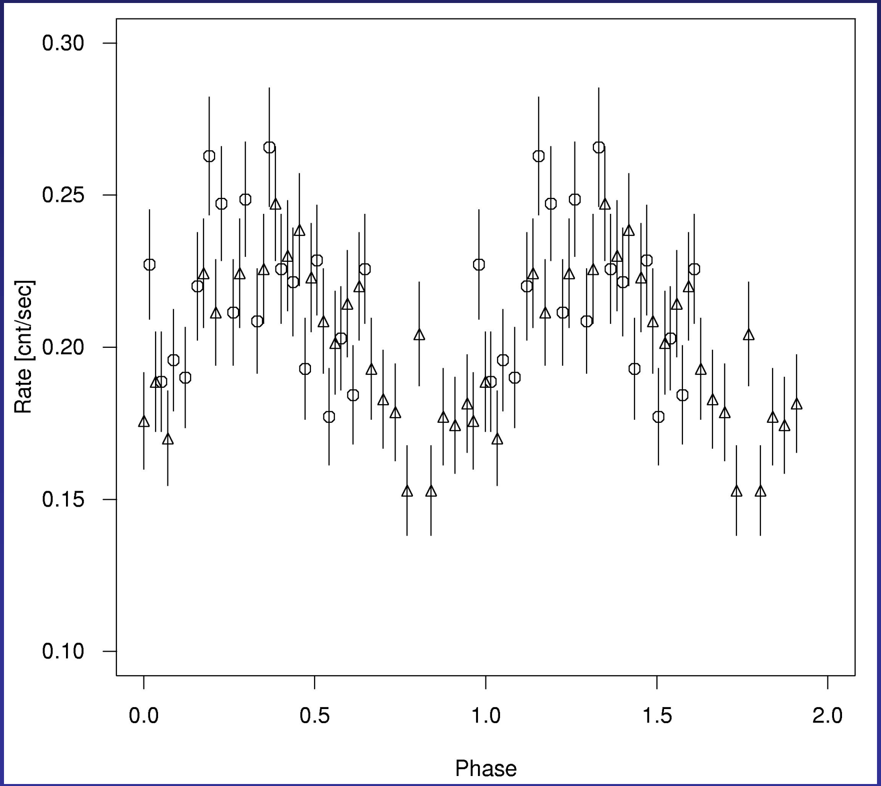
Major question: Do solar concepts apply?
Are stellar coronae "compact" or "extended"?

Coronal Structure

X-RAYS: Principle: Rotational modulation

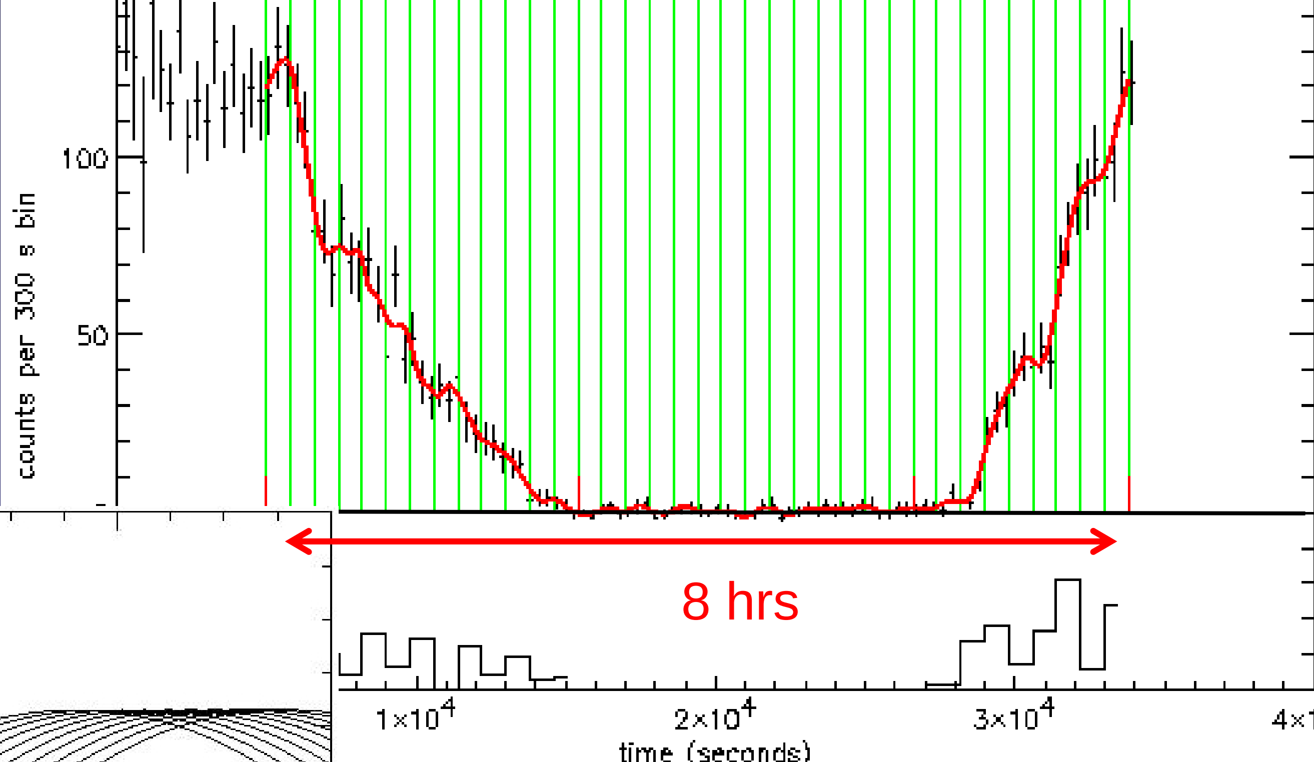


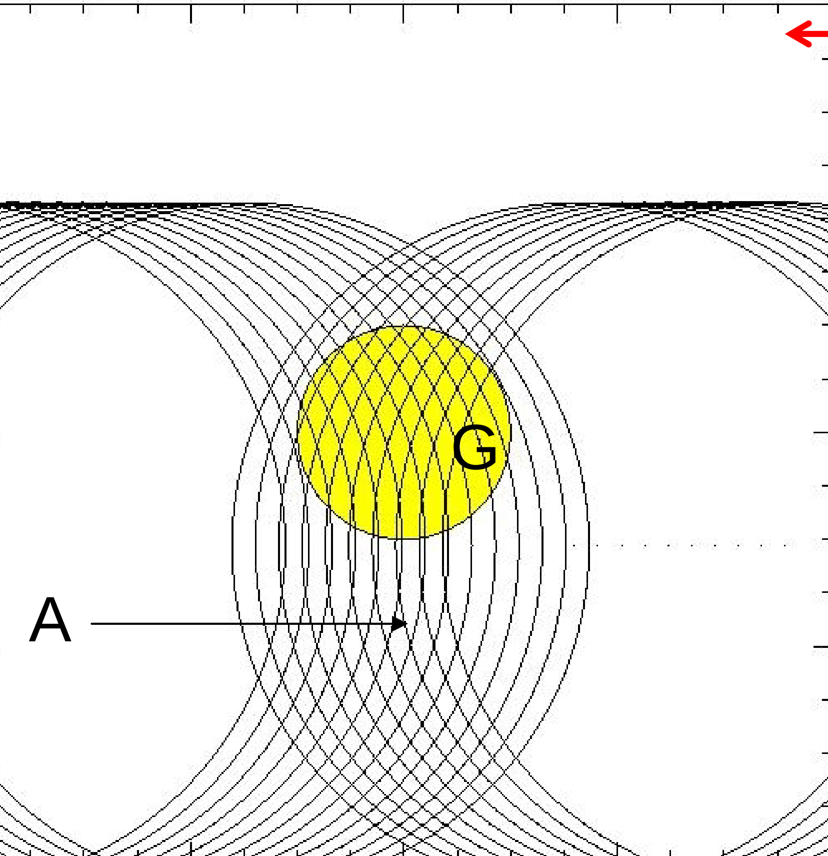
(Güdel et al. 1995)



(Marino et al. 2003)

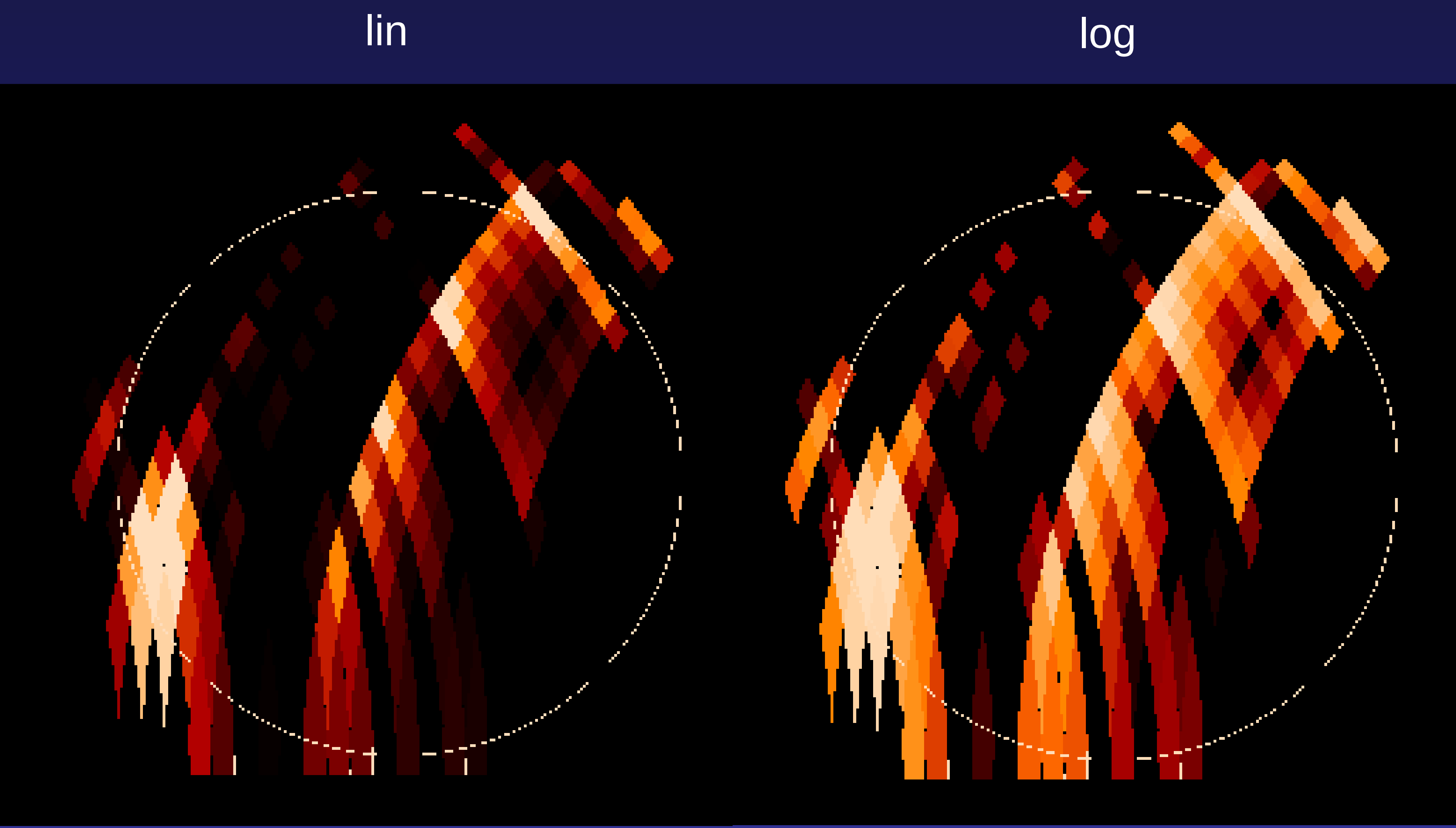
X-RAYS:
Principle: Eclipses





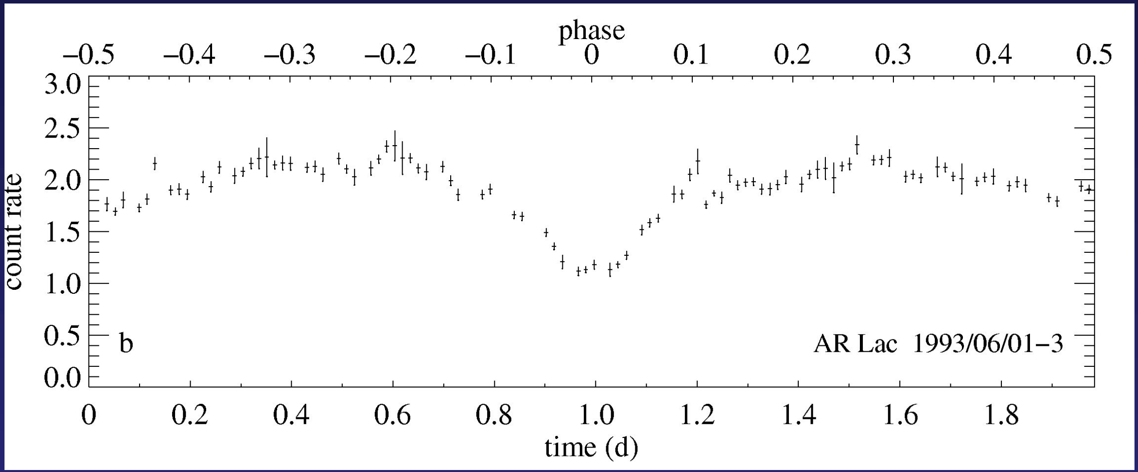
Total stellar X-ray eclipse
of α CrB (A0 V + G V)

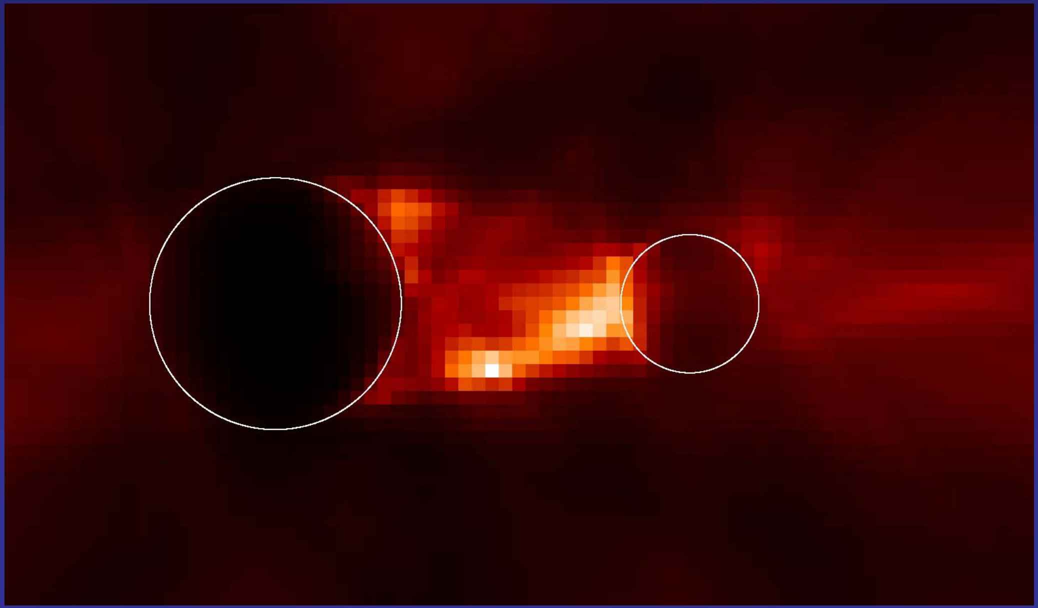
(Güdel et al. 2004)



solar-like active regions, densities < few times 10^{10} cm^{-3} (Güdel et al. 2004)

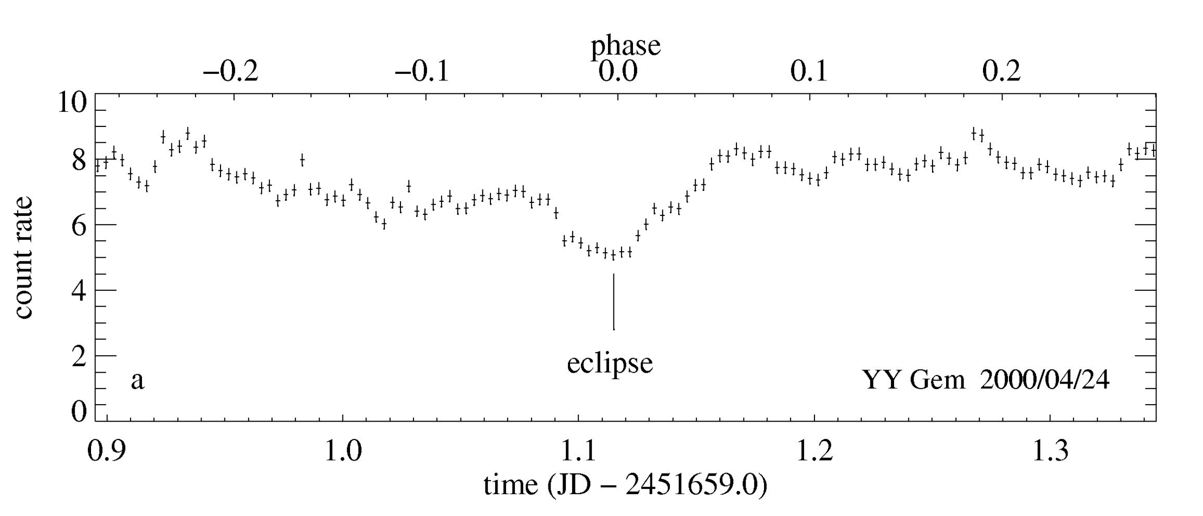
AR Lac in X-rays: 3-D modeling using Withbroe method (Siarkowski et al. 1993)

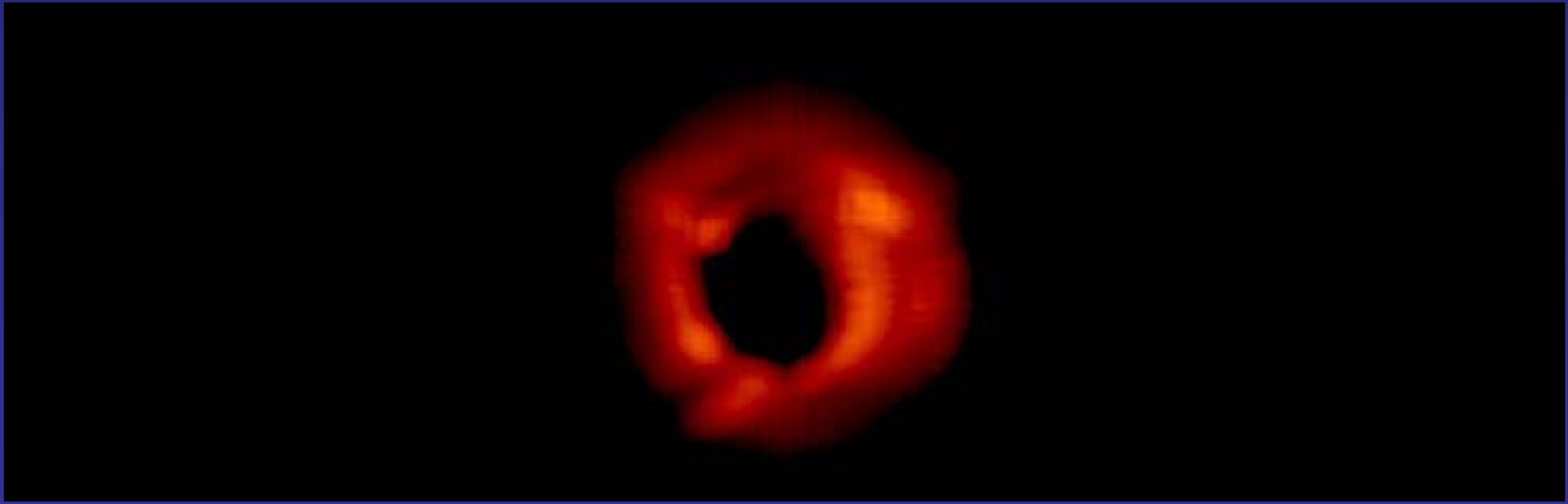




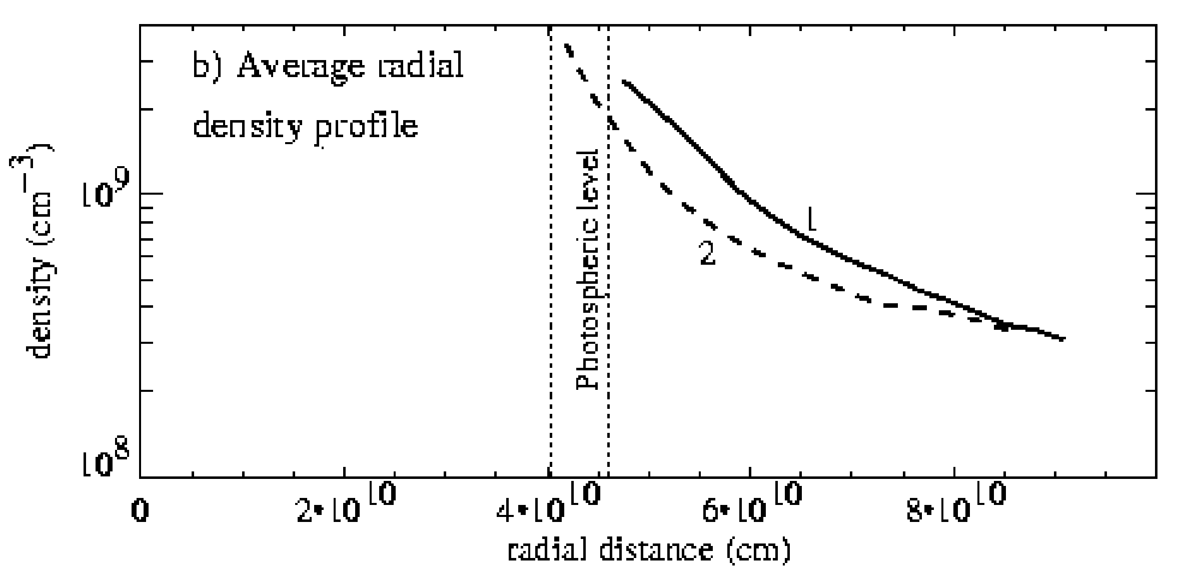
intrabinary magnetic fields?

YY Gem in X-rays: 3-D modeling using Withbroe method (Güdel et al. 2001)





no intrabinary emission required



Scale height (≈ 10^{10} cm)

$kT/(\mu m_H g)$

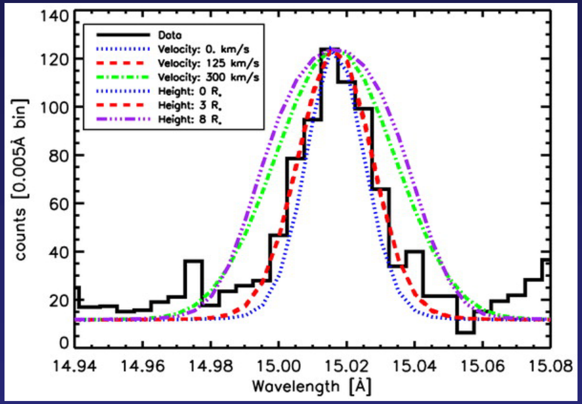
$\rightarrow T \approx 6\text{-}7$ MK

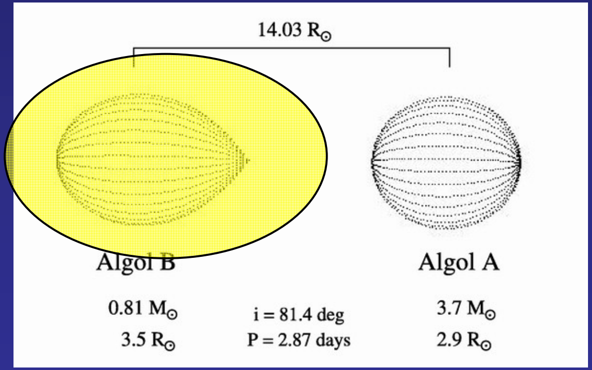
spectroscopically

measured: 3-10 MK

Coronal structure from line shifts and broadening

Algol (K2 IV + B8 V): (Chung et al. 2004)



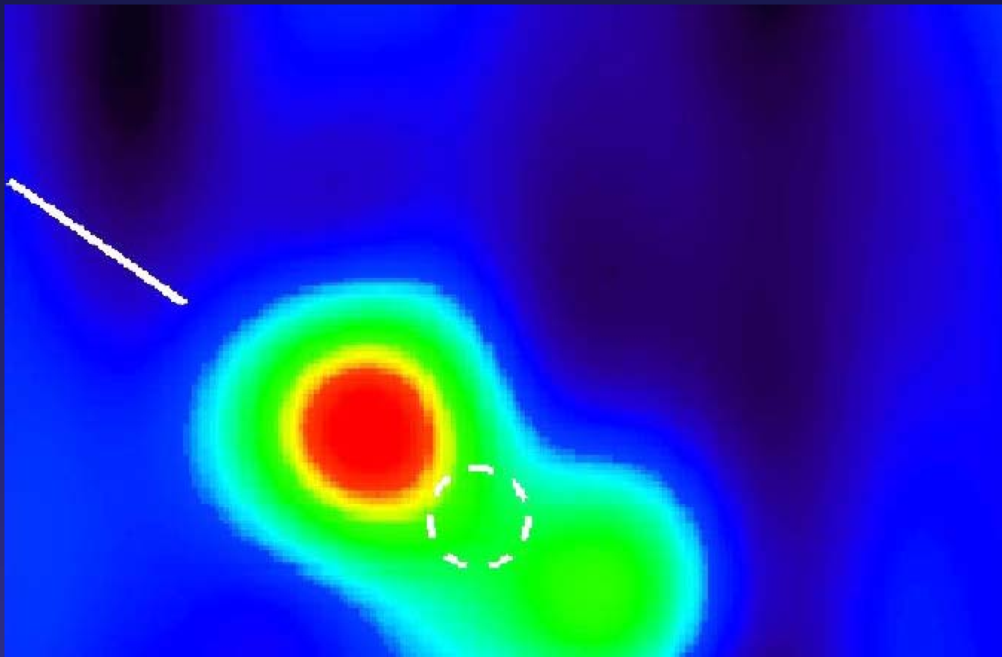


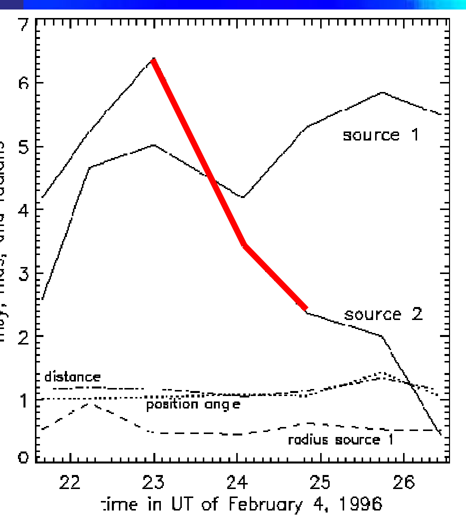
<u>excess line broadening:</u> Rotational broadening, implying **X-ray** coronal scale height ≈ R*
≈ thermal scale height

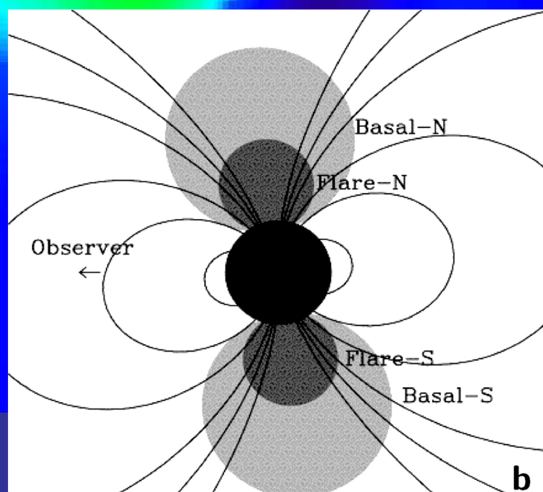
Similar for single stars:

Hussain et al. (2005) for AB Dor:
Coronal X-ray/FUV emission within ≈0.5 R_* (scale height for 10 MK)

Determining coronal structure with radio waves







(Mutel et al. 1998)

UV Cet, a nearby M dwarf

Brightness temp. 10^8-10^9 K

not thermal !
Gyrosynchrotron

Emissivity $\eta(B, N, \delta)$, $\delta \approx 2.5$
$\rightarrow B = B(N)$

- magnetic confinement
- $\nu = 2.8 \times 10^6 \, B\gamma^2$ [Hz]
- $\gamma B^2 = 6.7 \times 10^8 / t_{syn}$

B = 15-113 G, $n_e < 2 \times 10^8$ cm^{-3}

(Benz, Conway, Güdel 1998)

V773 Tau millimeter observations
Periodic radio flares (Massi et al.):

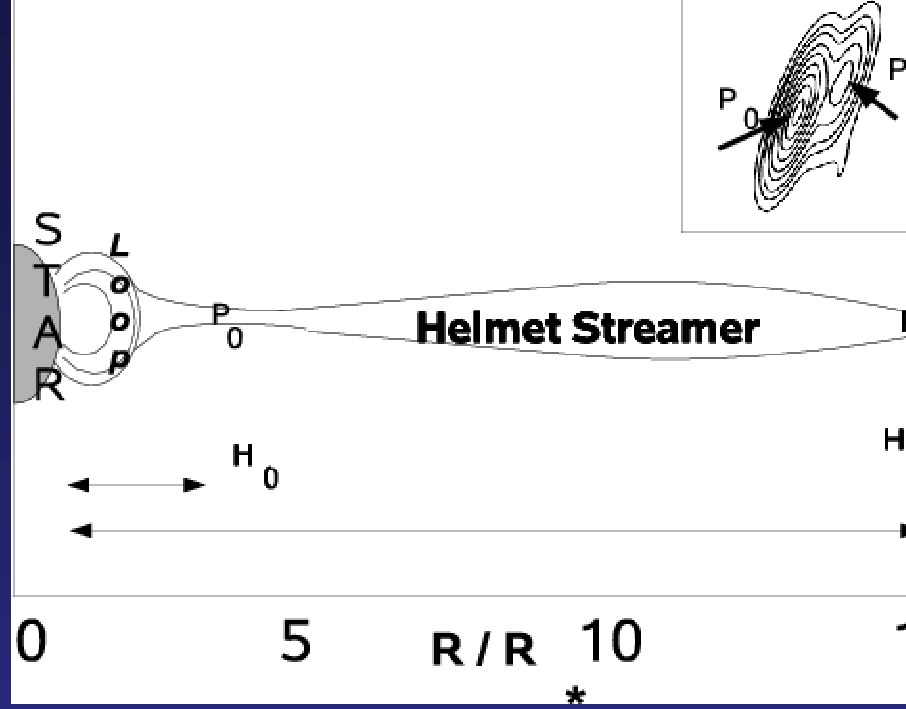
Size scale from VLBI: > 15 R_*

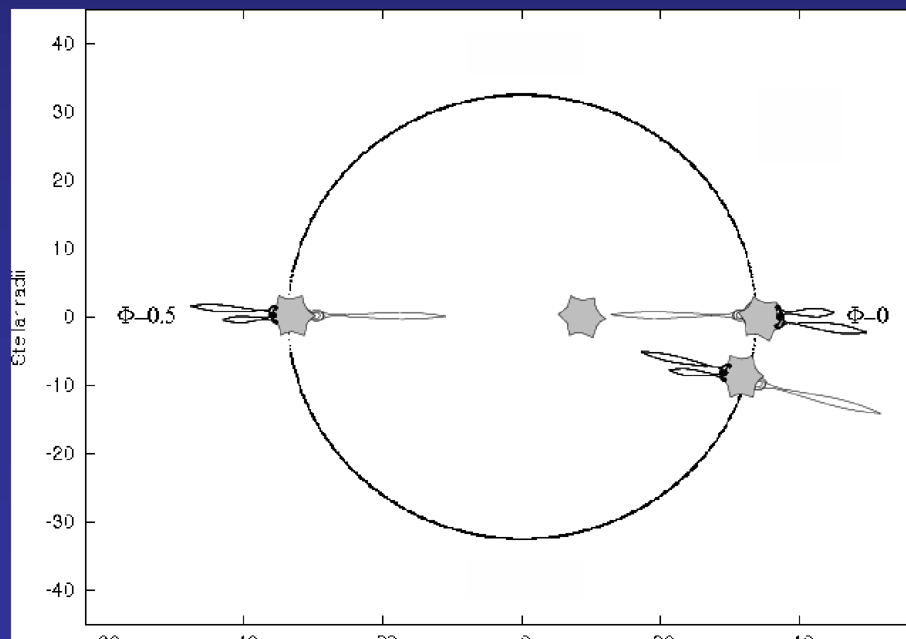
Pitch angle scattering in helmet streamers?

combine with VLBI info and periodic flaring (at periastron):

Helmet streamers interacting with companion star?

$\gamma = 20 – 632$, $B < 1$ G at apex
→ large-scale!





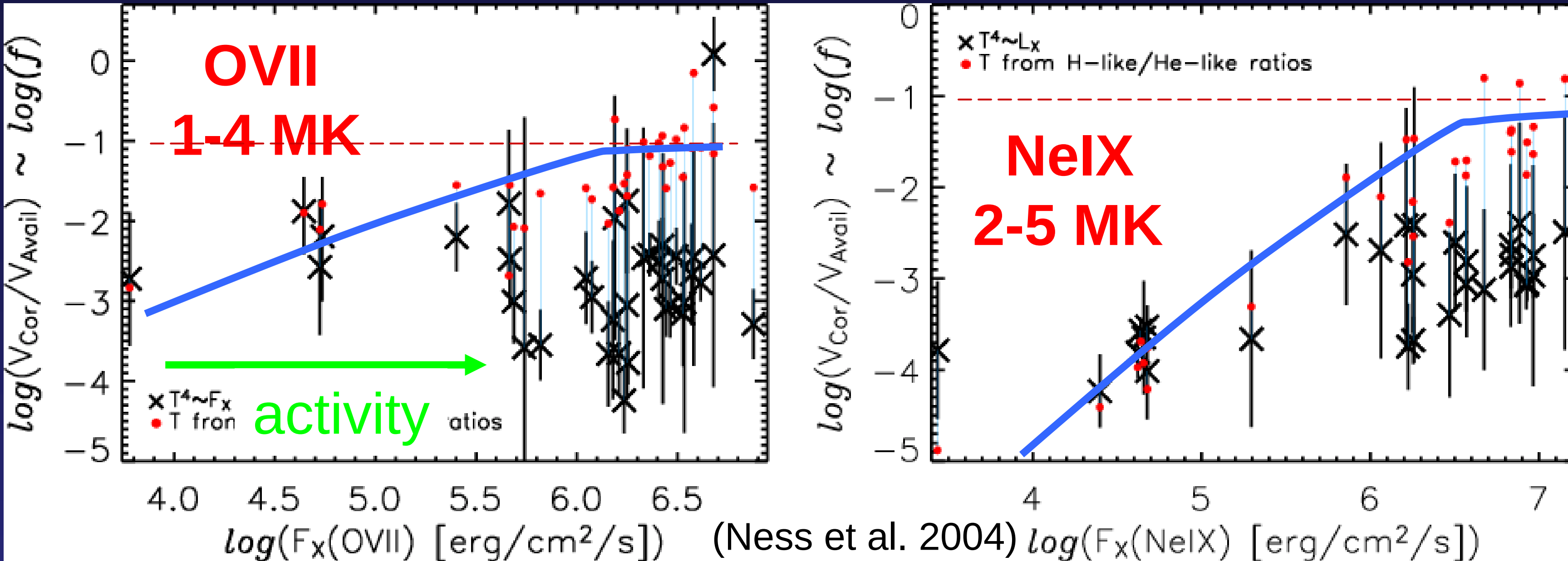
Coronal Structure: Summary and suggestions:

- Define ***what*** coronal structure:

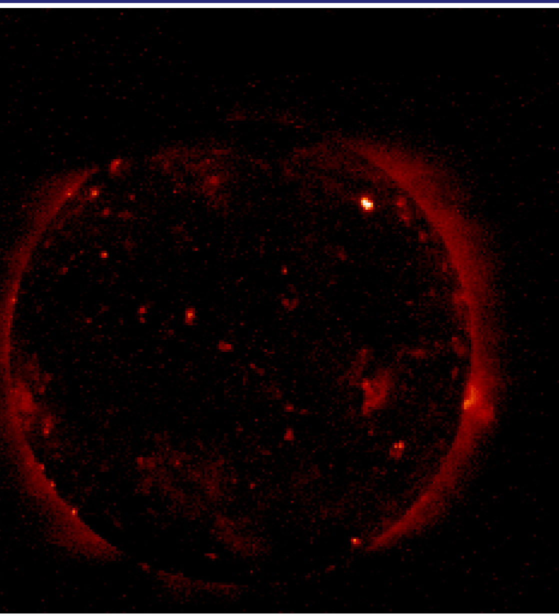
  * the closed magnetic field lines?
  * the trapped, dense, hot plasma?
  * the loops with trapped, high-energy particles?

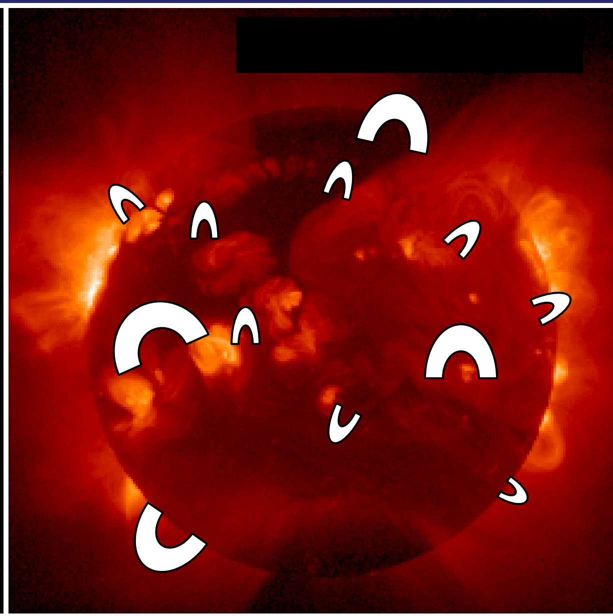
- Clear evidence for hot material on size scales of of a *pressure scale height* *(could it be different?)*

- Clear evidence for *large-scale magnetic fields* in magnetically active stars and binaries as judged from radio tracers (relativistic electrons; radio polarization)



(Ness et al. 2004)



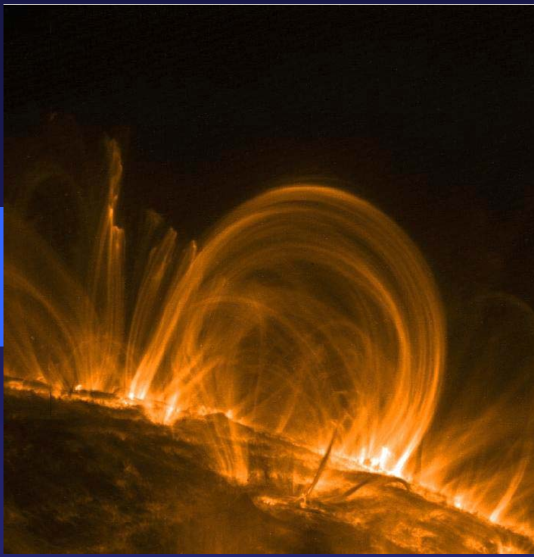


More magnetic interaction → flaring:

hot, dense
(→ high-luminosity)
component

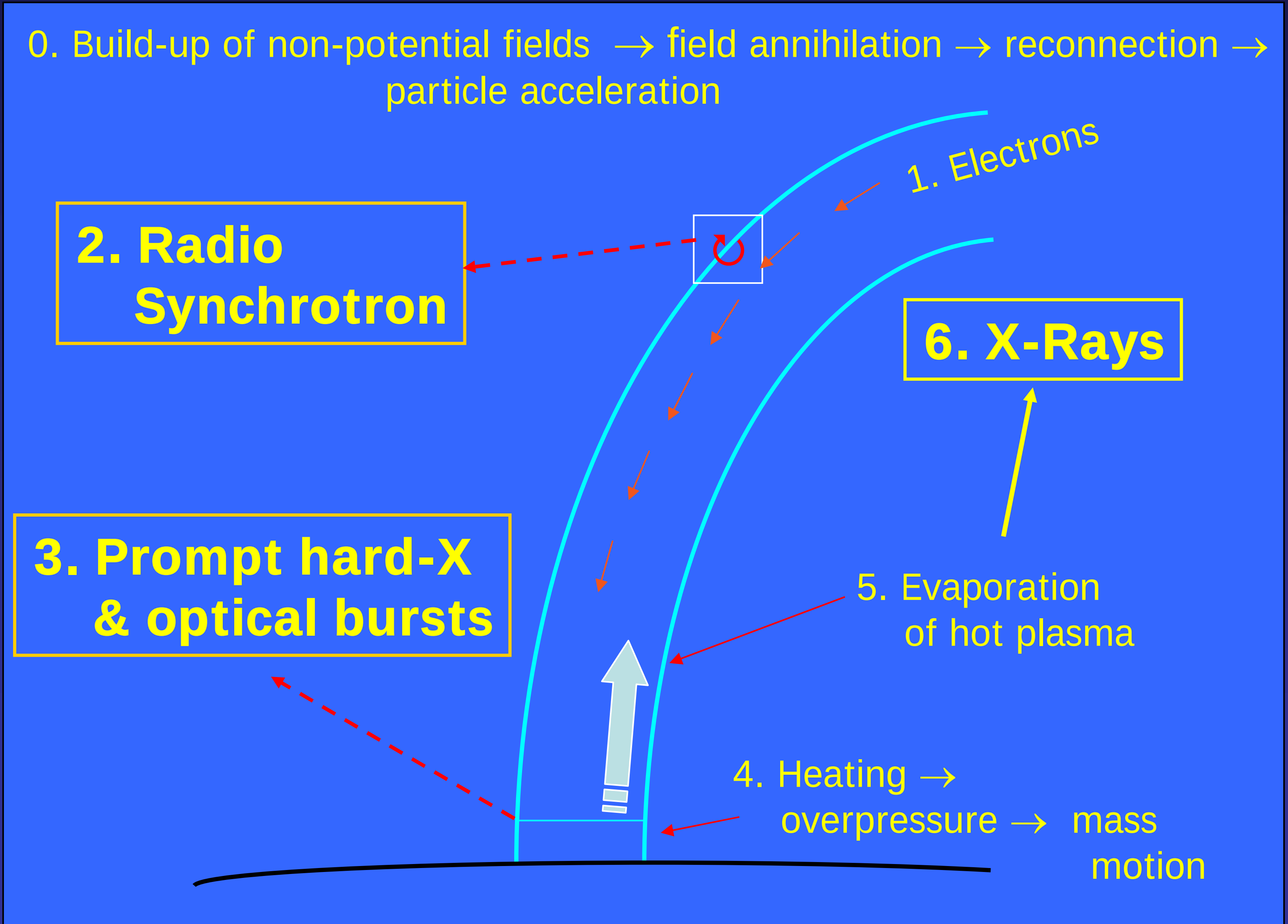
(Güdel et al. 1997, Drake et al. 200
Ness et al. 2004, Testa et al. 2004)

Coronal Flares



Are giant stellar flares analogs to solar flares?

Standard flare scenario after reconnection



Bonn,

approximation for radiative loss time >> energy release time

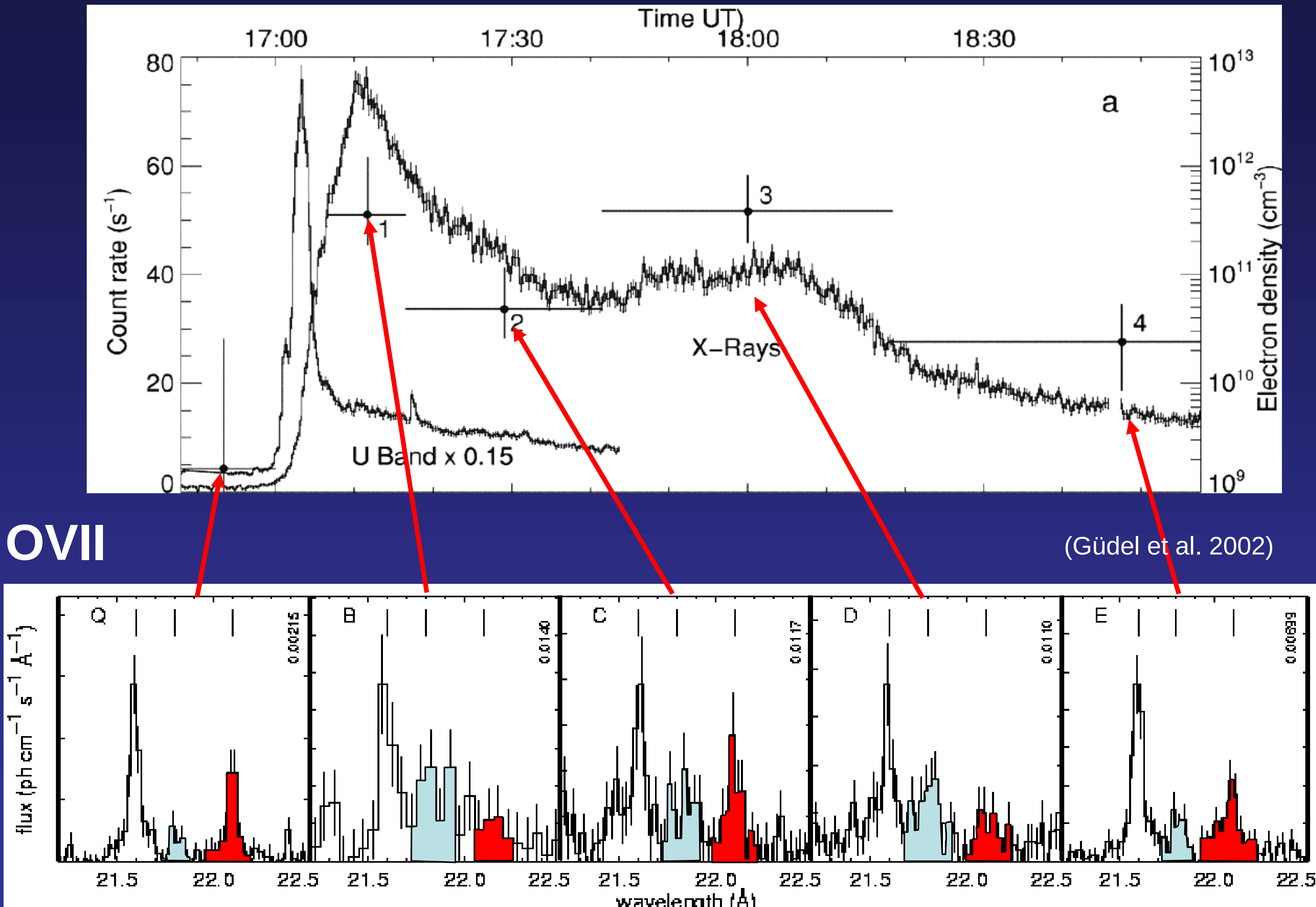
$$\frac{d}{dt}(3n_e kTV) \quad \propto \quad \text{electron flux} \quad \propto \quad L_R$$

$$\frac{d}{dt}L_X \quad \propto \quad L_R$$

"Neupert Effect"

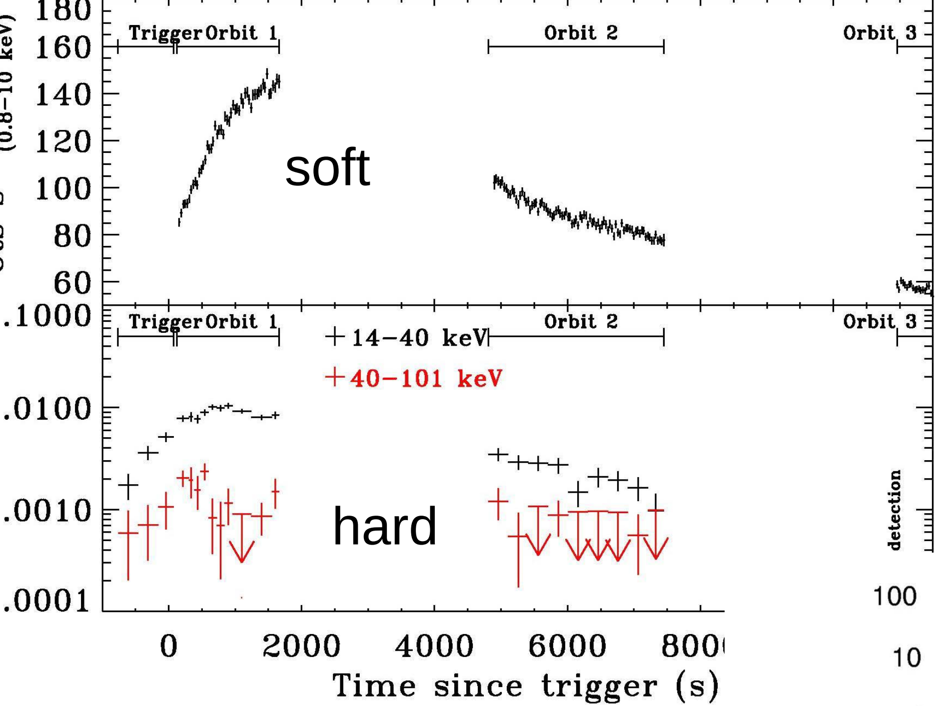
(the proportionality between thermal energy content and radiative loss is a crude approximation)

OVII



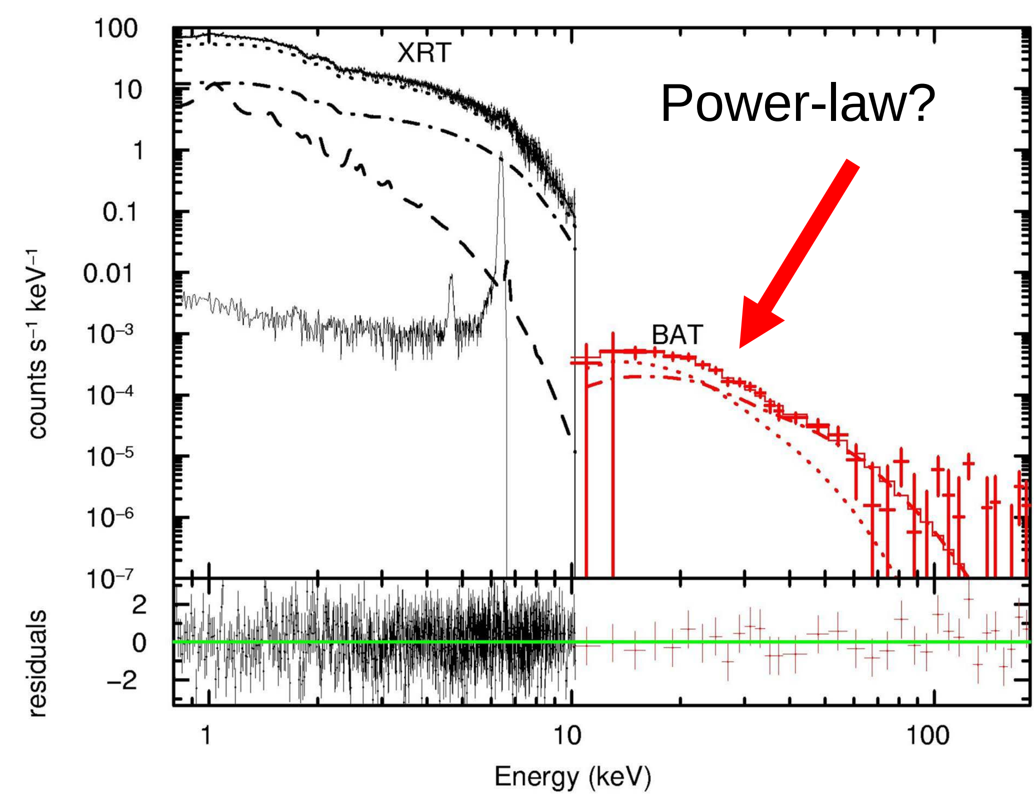
(Güdel et al. 2002)

$5x10^9$	$4x10^{11}$	$2x10^{10}$	$4x10^{11}$	$2x10^{10}$



First detection of non-thermal hard X-ray emission in stellar flares (by SWIFT):

(*to be expected* judged from non-thermal radio emission)



(Osten et al. 2006)

Counter-examples:

EV Lac (Osten et al. 2005)

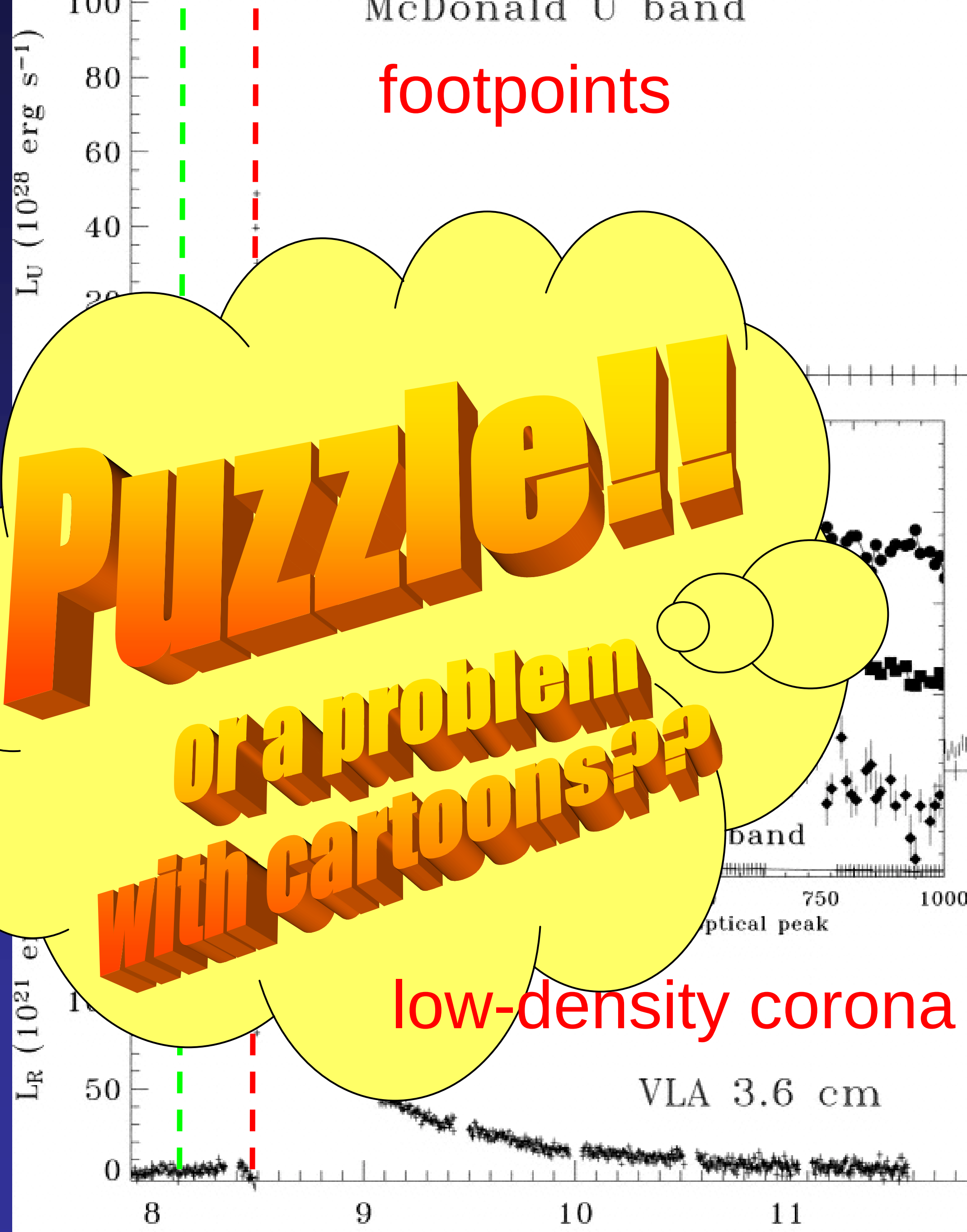
- no heating of / evaporation to corona?

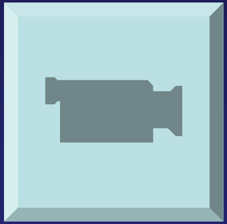
- perfect trapping of electrons in corona (BUT: U band?)

- coronal flare of very low density?

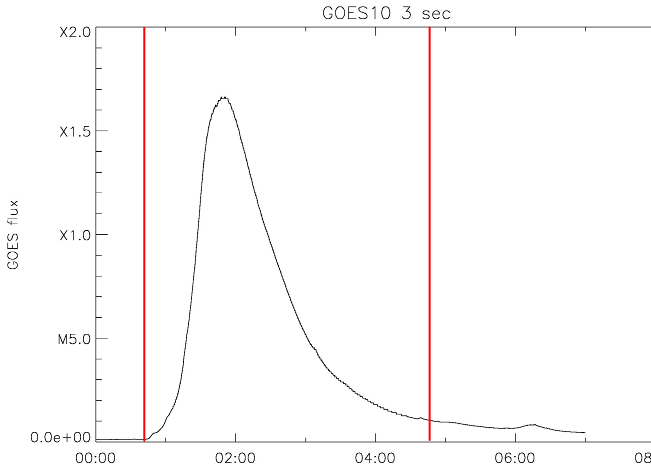
- shadowing of some source

- very-high energy particles penetrate deep into photosphere: no evaporation?



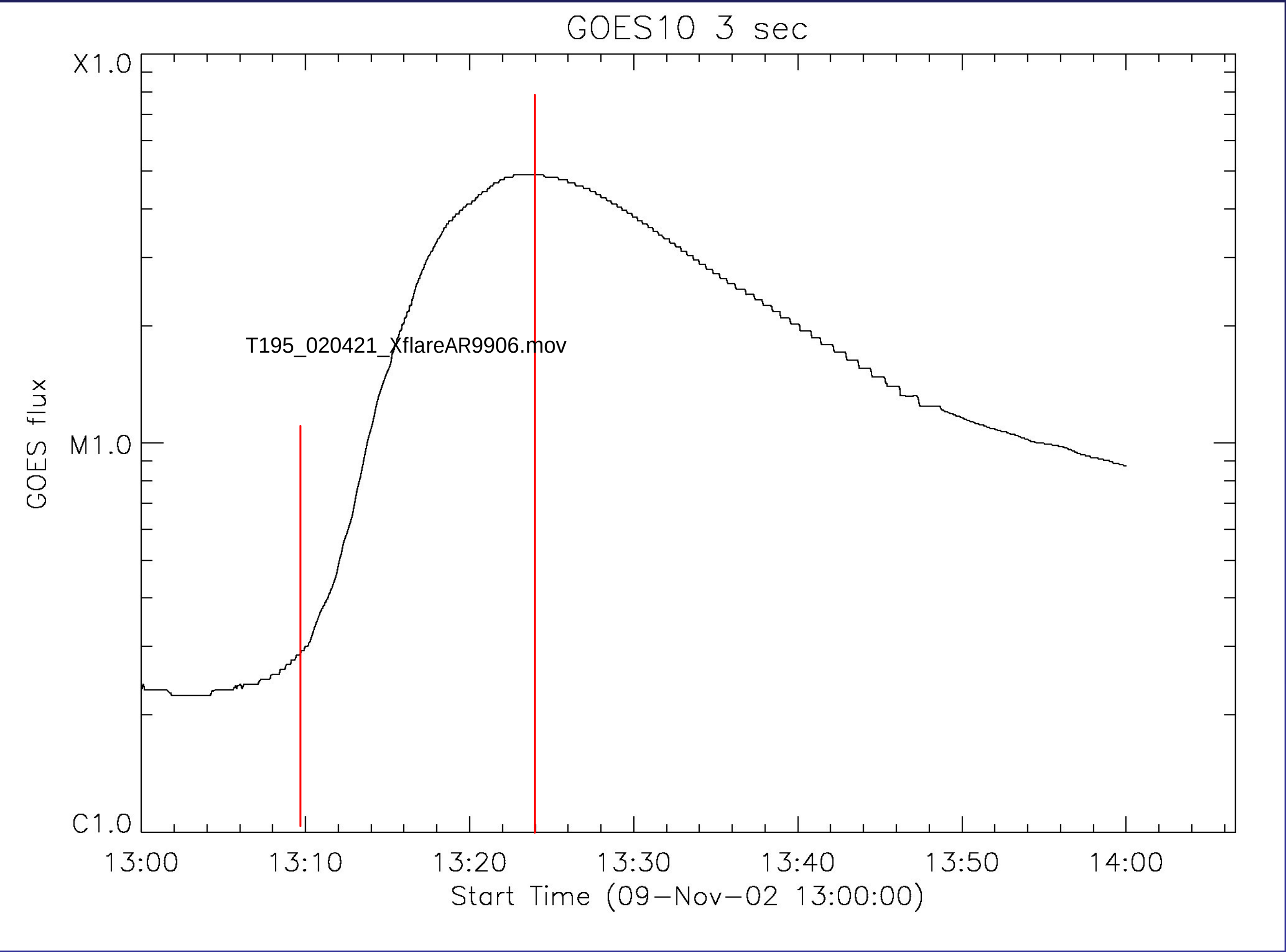


T195_020421_XflareAR9906.mov



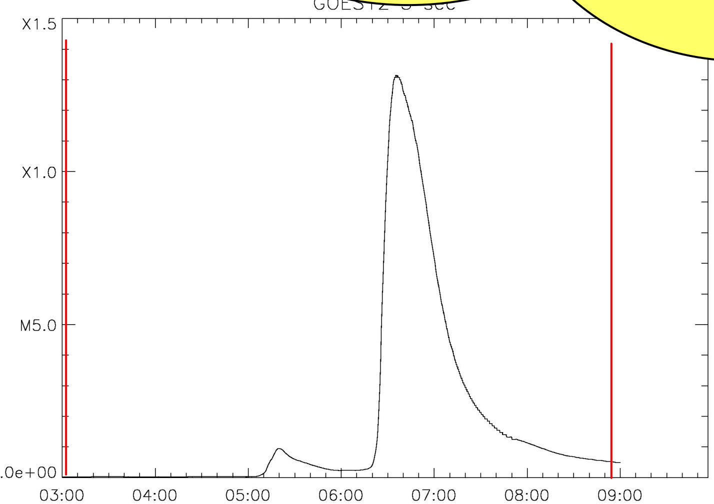
Hard X-ray footpoint motion: evolution of an arcade

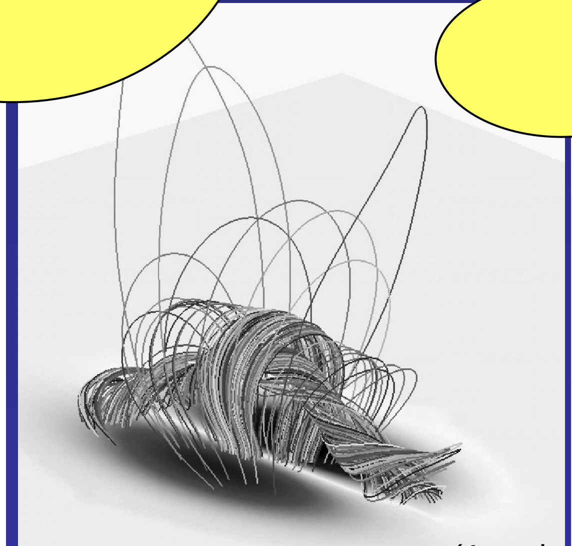
(moveitloop.mpg
coutesy of
Paolo Grigis, ETHZ)



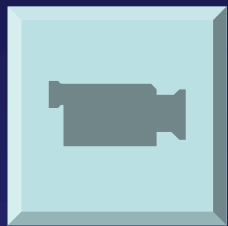
Flares are complicated!

T171_20050730_03X.mov

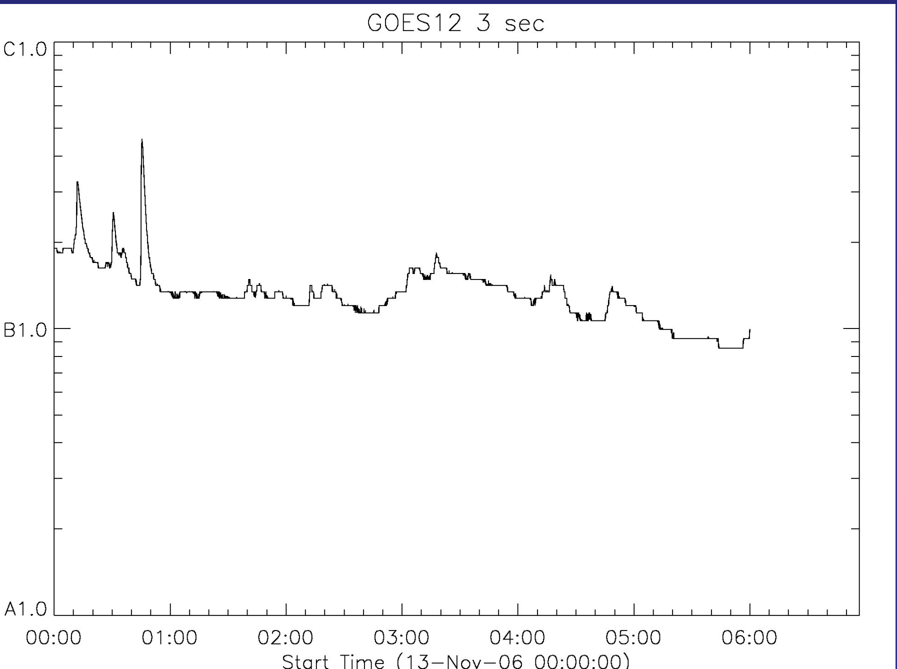


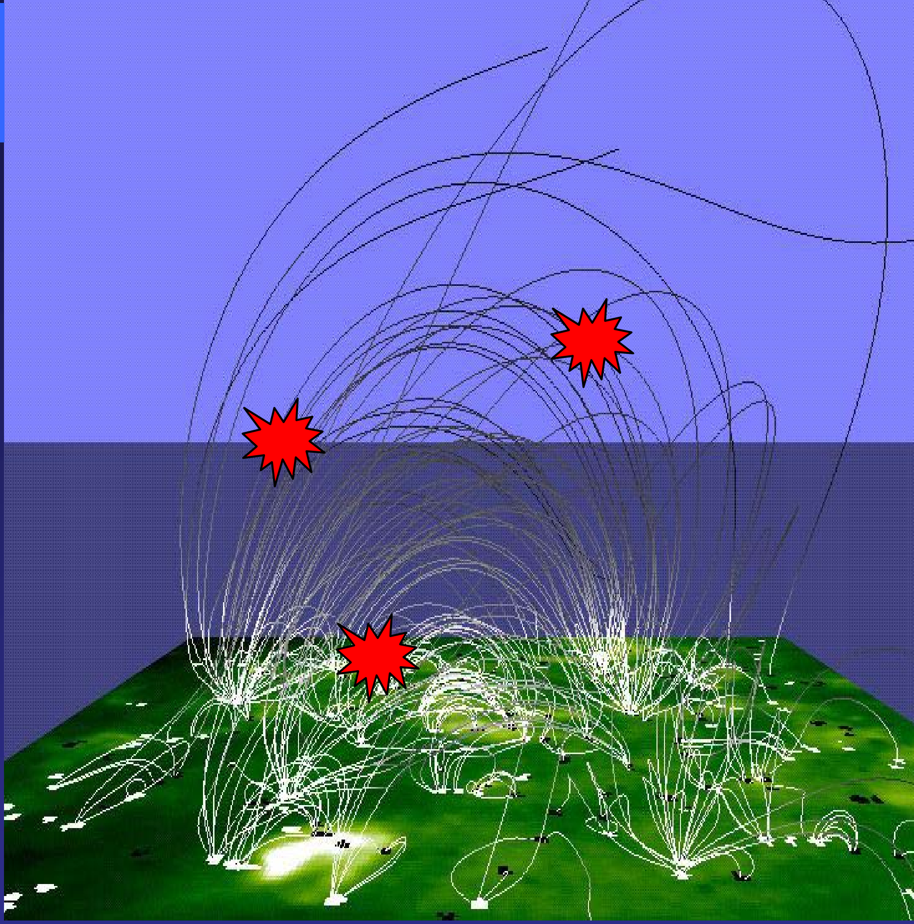


Continuous Flaring (?)

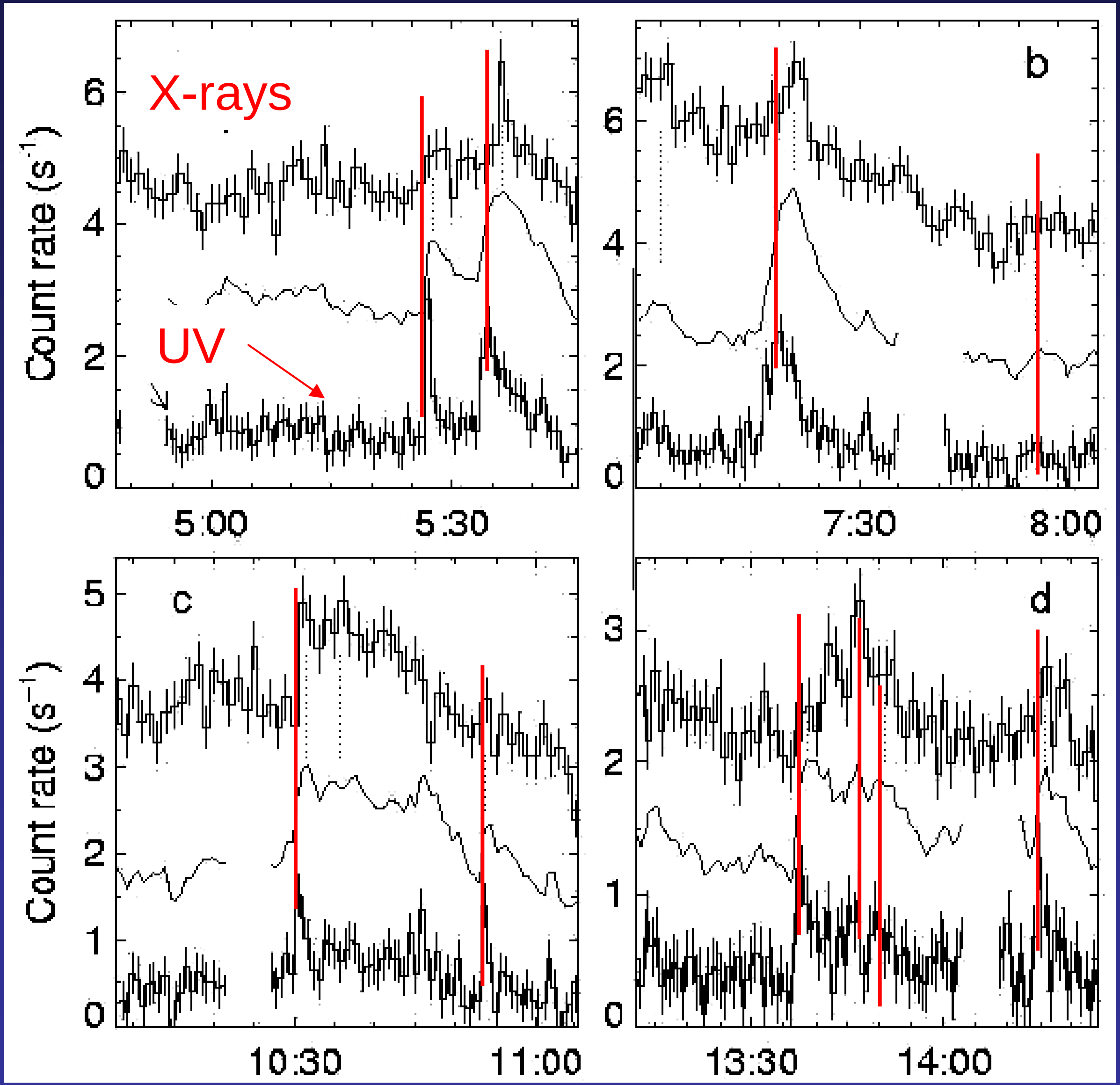


Solar guidance:





Smallest stellar flares seen in X-rays: Proxima Centauri



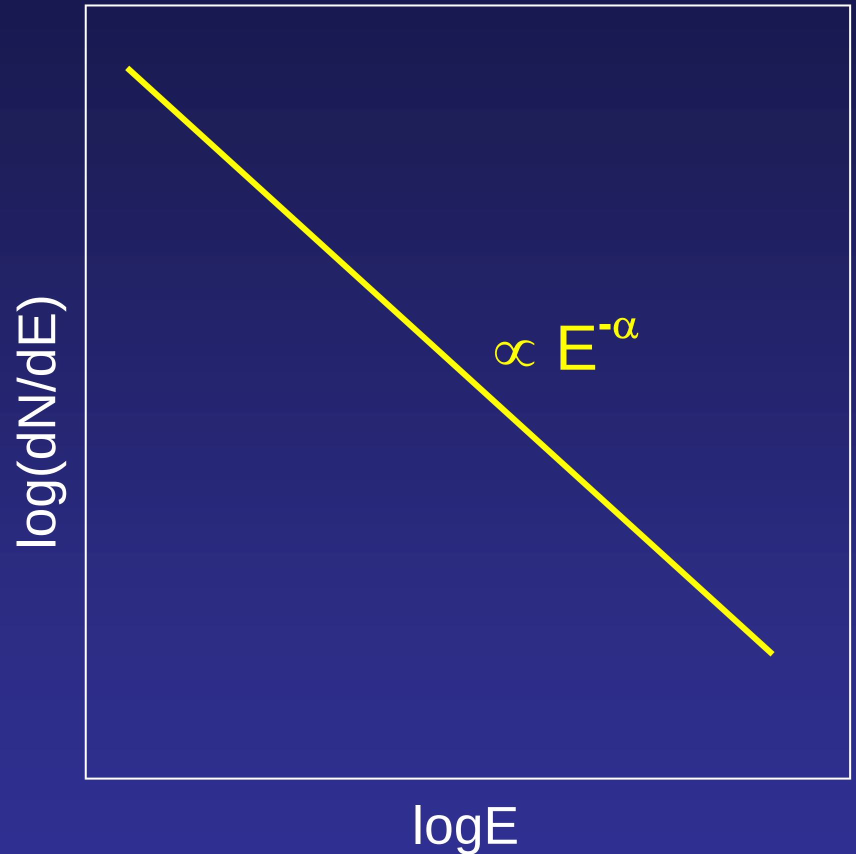
(Güdel et al. 2002)

FLARE ENERY DISTRIBUTIONS

$dN/dE \propto E^{-\alpha}$

$L_X \propto \int_{E1}^{E2} E \, dN/dE \, dE$

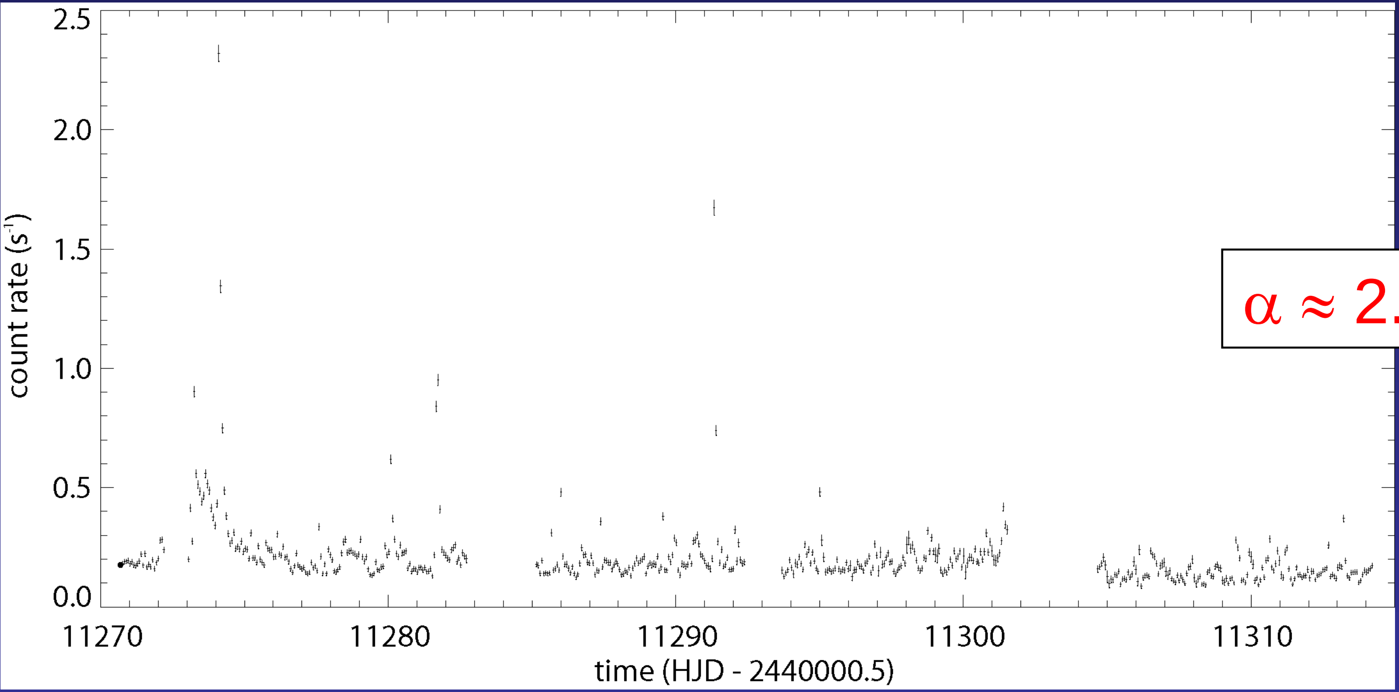
$\alpha \geq 2$: divergence for $E1 \rightarrow 0$ ("microflares")



In that case, all of the observed (quasi-steady) emission "may be" due to the superposition of small flares

Statistical tests of light curves show that $dN/dE \propto E^{-\alpha}$ implies $\alpha > 2$

(Audard et al. 1999, 2000, Güdel et al. 2003, Kashyap et al. 2002, Arzner & Güdel 2004)



$\alpha \approx 2.1\text{-}2.3$

44 days

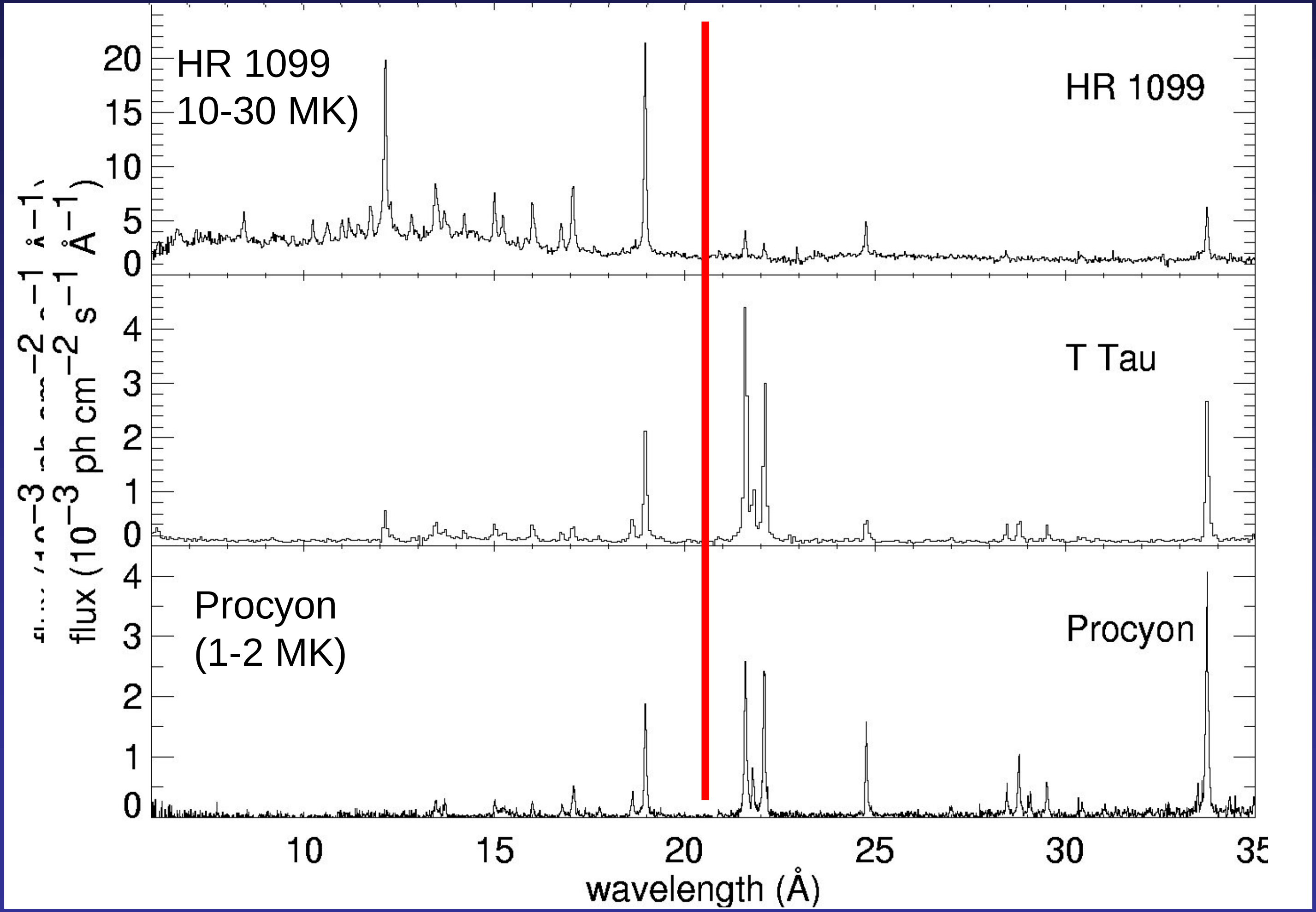
(Güdel et al. 2003)

$dN/dE \propto E^{-\alpha}$

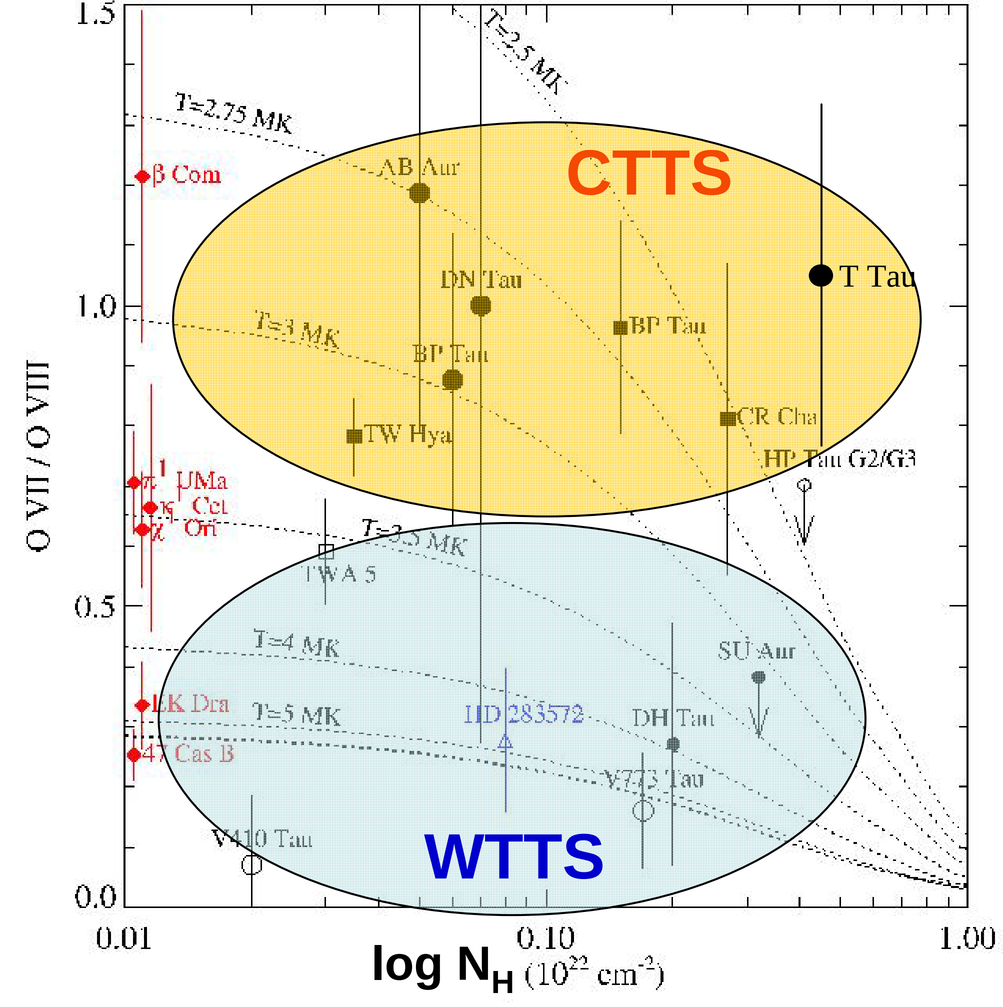
Collura et al. 1988	$\alpha \approx$ 1.52 +/- 0.08	M dwarfs
Pallavicini et al. 1990	$\alpha \approx$ 1.7 +/- 0.1	M dwarfs
Osten et al. 2000	$\alpha \approx$ 1.6	RS CVn
Audard et al. 1999, 2000	$\alpha \approx$ **2.2** +/- 0.2	G,K,M dwarfs
Kashyap et al. 2002	$\alpha \approx$ **2.0-2.7**	M dwarfs
Güdel et al. 2003	$\alpha \approx$ **2.0-2.5**	AD Leo
Arzner & Güdel 2004	$\alpha \approx$ **2.3** +/- 0.1	AD Leo
Wolk et al. 2005	$\alpha \approx$ 1.7	TTS (Orion)
Stelzer et al. 2007	$\alpha \approx$ **2.4** +/- 0.5, 1.9 +/- 0.2	TTS (Orion, TMC)

Should stellar coronal models really be (stochastic-) flare models?

"Anomalous" Coronal Heating?



N_H removed



O VII/O VIII Ly α

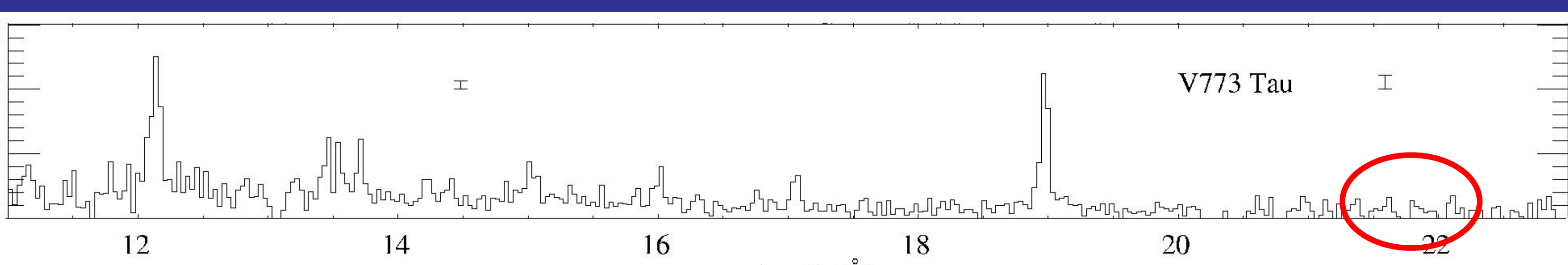
low in CTTS

high in WTTS

"SOFT EXCESS"

(1-3 MK; Telleschi et al. 2007, Güdel et al. 2007)

accretion-related?



Brown Dwarfs: A Low-Mass "Coronal" Puzzle

Young brown dwarfs: "low-mass T Tau objects on Hayashi track"

Old brown dwarfs: T_{eff} down to < 1000 K
convection ceases
no nuclear energy source

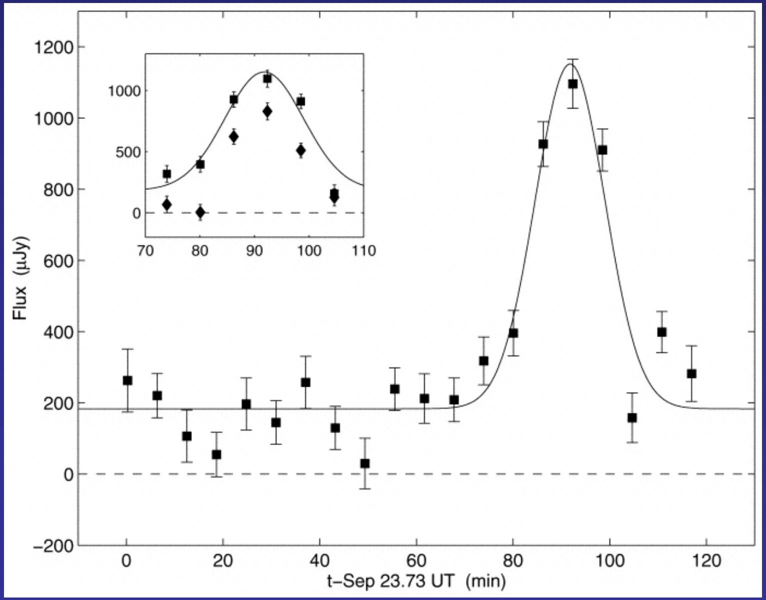
Expect: **Drop in magnetic activity**
Inefficient heating and particle acceleration

A few initial surprises (cont'd):

Radio emission from field brown dwarfs

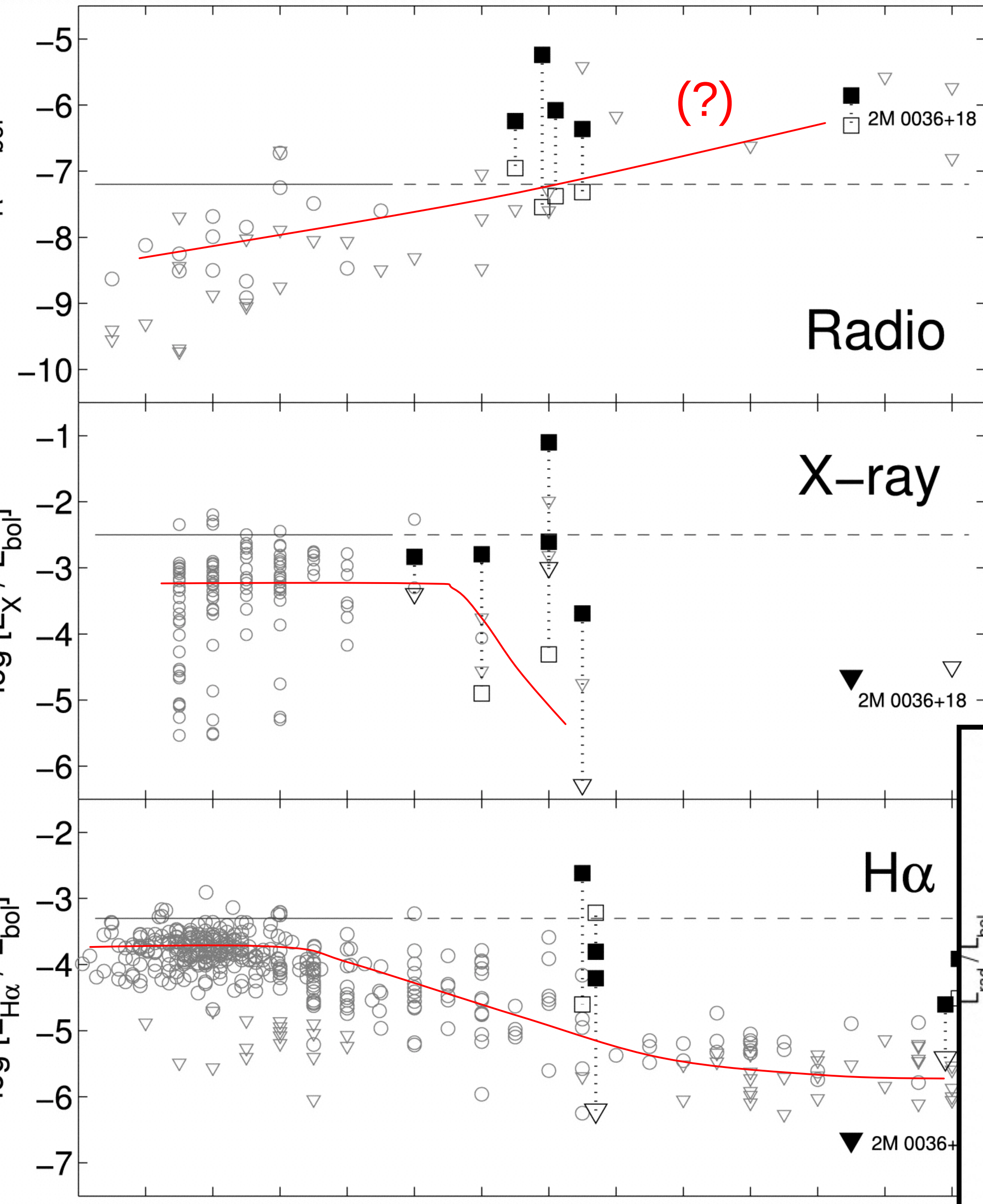
strong, "steady" and flaring emission as in M dwarfs (Berger 2001/03/06, Berger et al. 2005, Burgasser & Putman 2005)

gyrosynchrotron emission in B ≈ 100 G



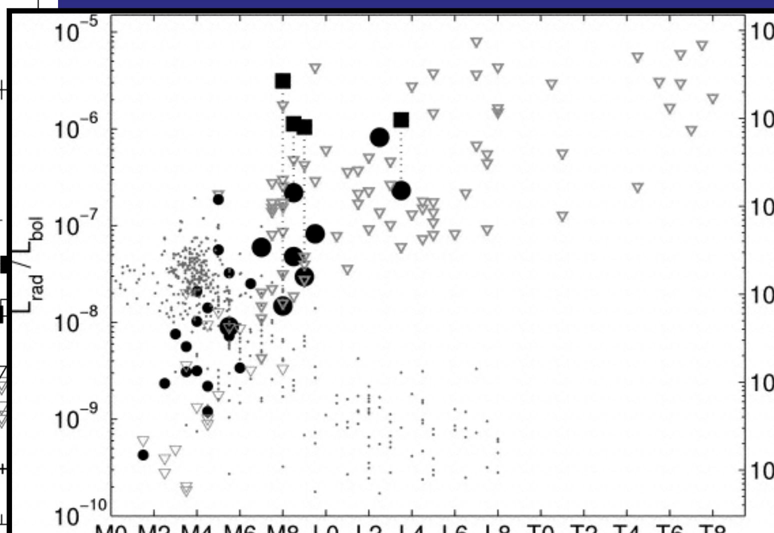
(Berger 2002)

Putting BDs into context:

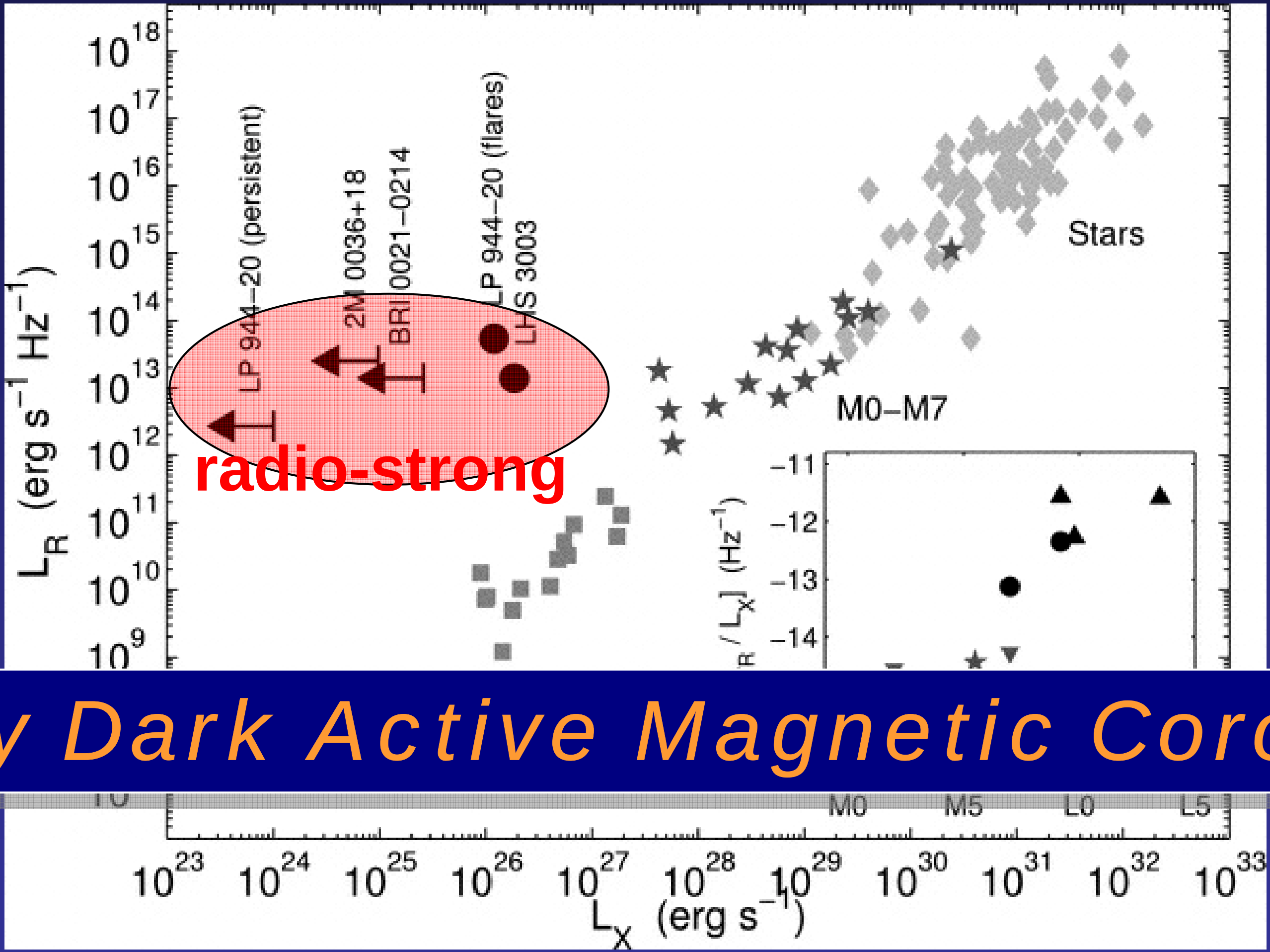


BD magnetic coronal energy release predominantly in accelerated particles!

(Berger et al. 2005, Berger 2006)



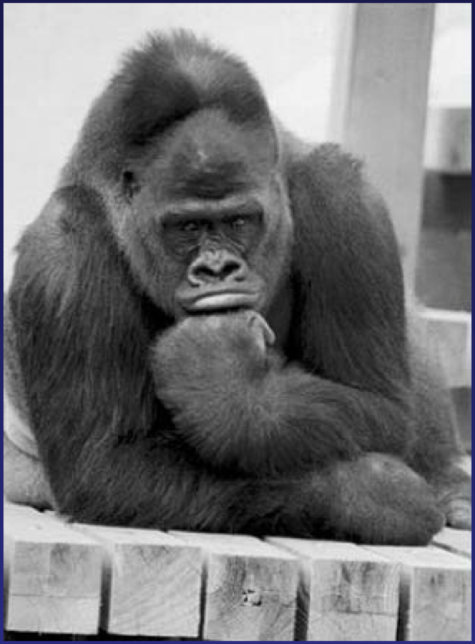
Putting BDs into context:



"X-Ray Dark Active Magnetic Coronae?"

(Berger 2006)

Conclusions?



* X-ray coronae as the end product of a chain of energy release and transformation processes. We tend to see dense plasma within a scale height.

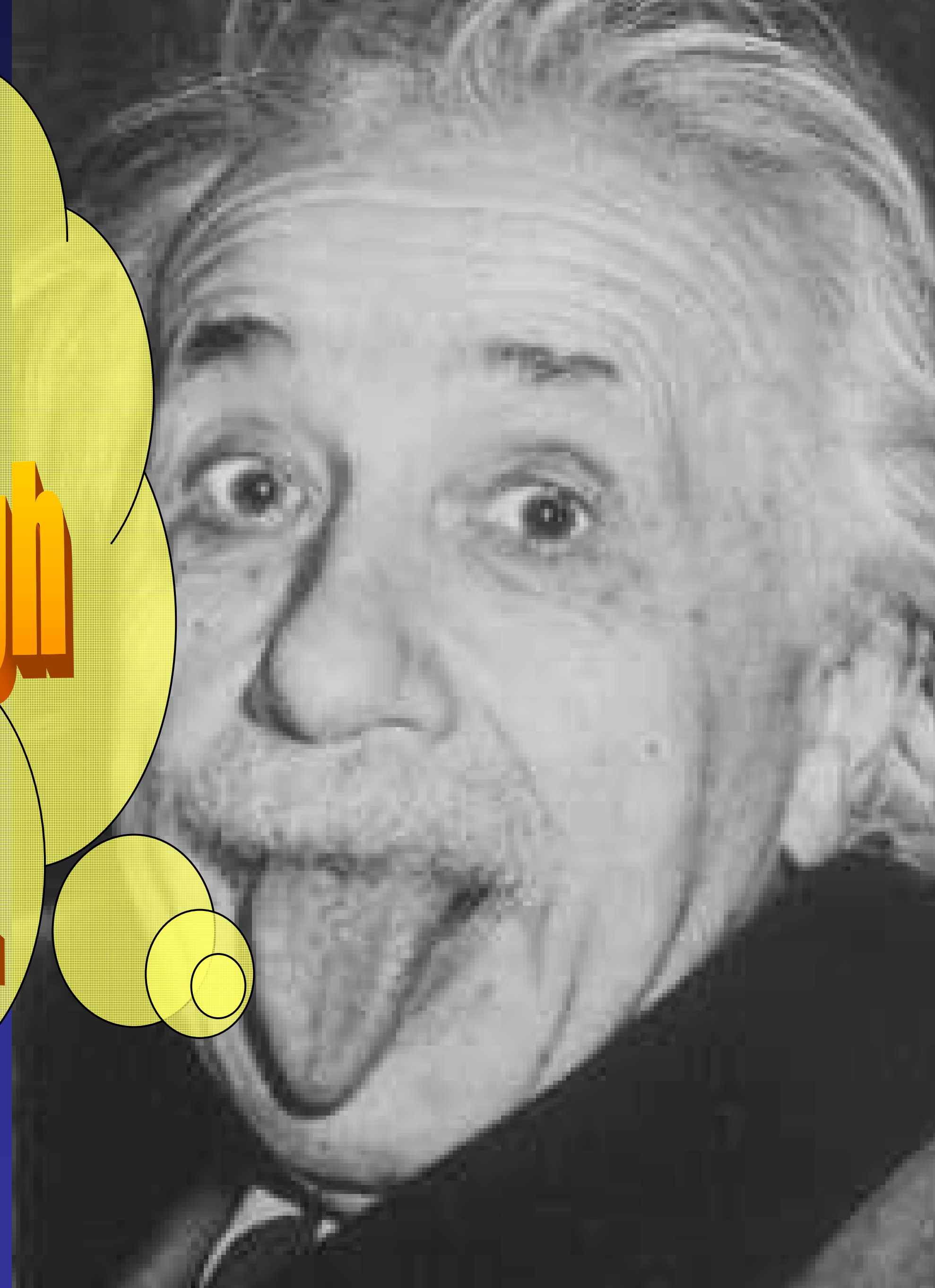
* There is clear evidence for much larger-scale magnetic fields from radio studies. Particle acceleration is a common and important phenomenon in active stars.

Many open problems to be addressed in detail, using the Sun as a guide:

- How are magnetic fields structured globally? and in flares?
- Are flares the ultimate energy source for active stellar coronae?
- Are there magnetically active X-ray dark coronae?   (BDs, TTS)
- Are stellar coronae modified by accretion processes and disks?

→Build in complexity!

Reality is merely an illusion, although a persistent one.



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