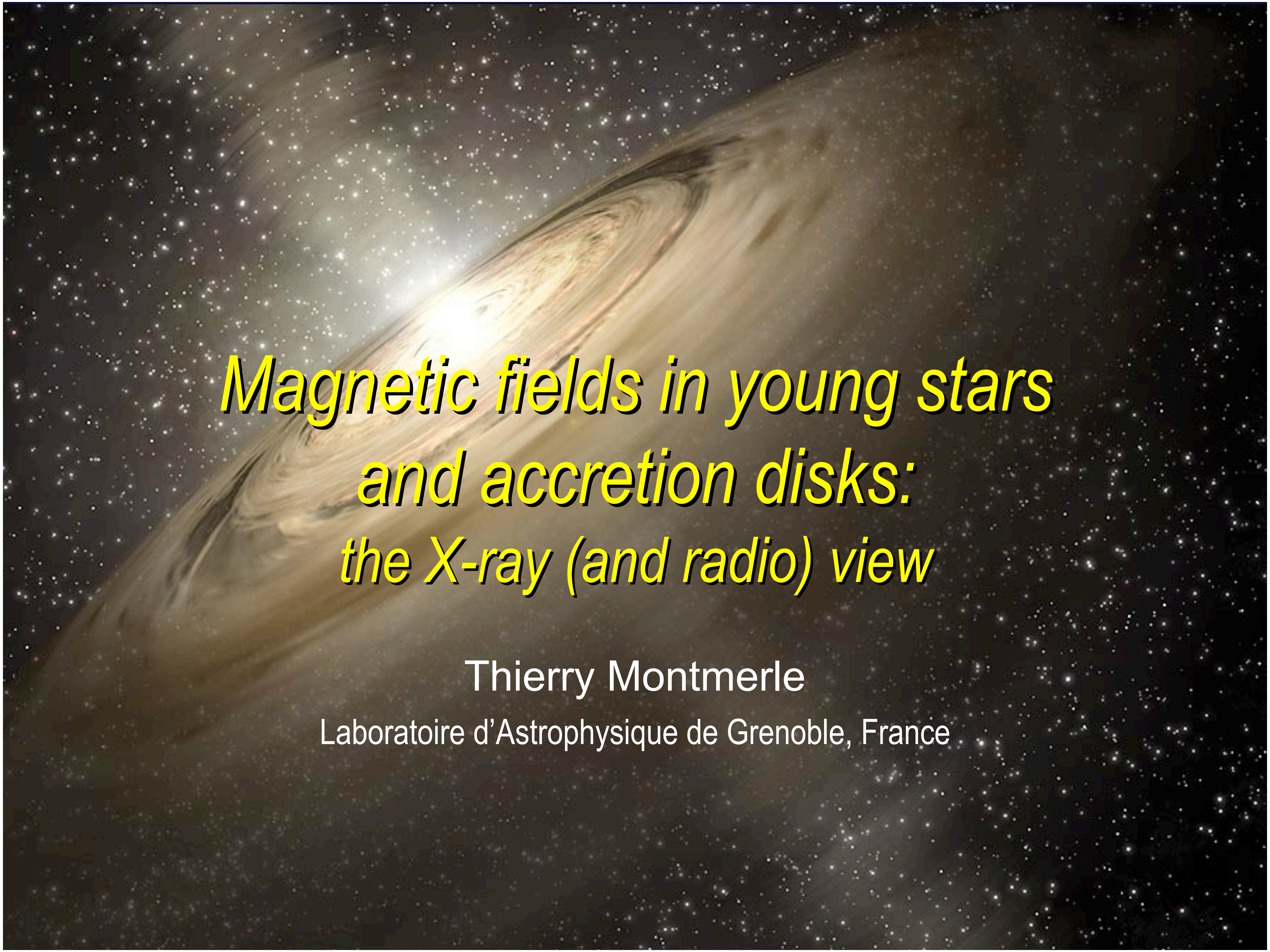

Magnetic fields in young stars and accretion disks:
the X-ray (and radio) view

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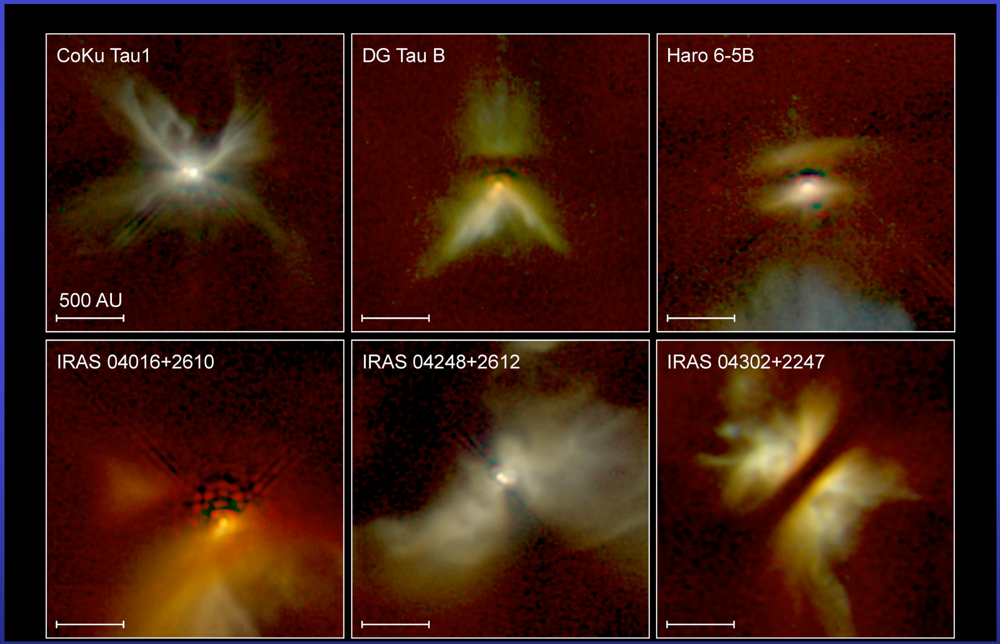
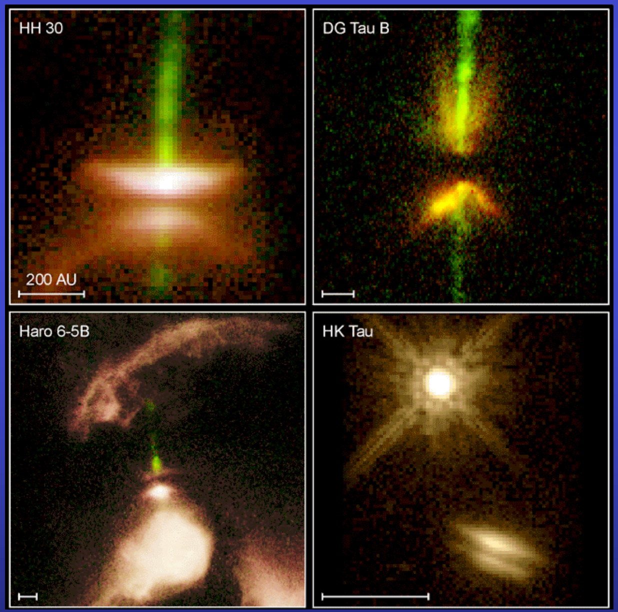
1. Low-mass and high-mass young stars: a brief review

- ~ 90% of stars (of all masses), and 100% of massive stars (~ 10-100 M_{Θ}) in the Galaxy form in *clusters* of > 100 stars (and *"OB associations"*, up to x 10^4 members…)
- Low-mass (~ solar) stars are much like… *AGNs* in their early stages ("Young Stellar Objects": accretion disks and jets !)
  - They are mostly, or entirely, externally *convective*, like the Sun
  - Convective movements create surface magnetic fields via the dynamo effect
- A fraction of high-mass stars are "magnetic", and are much like… *pulsars* (albeit slow !) (extended magnetospheres)
  - Massive stars (earlier than B3) have a convective core surrounded by an extended *radiative envelope*; their strong UV radiation generates powerful *winds*
  - The boundary are A stars: fully radiative, no winds

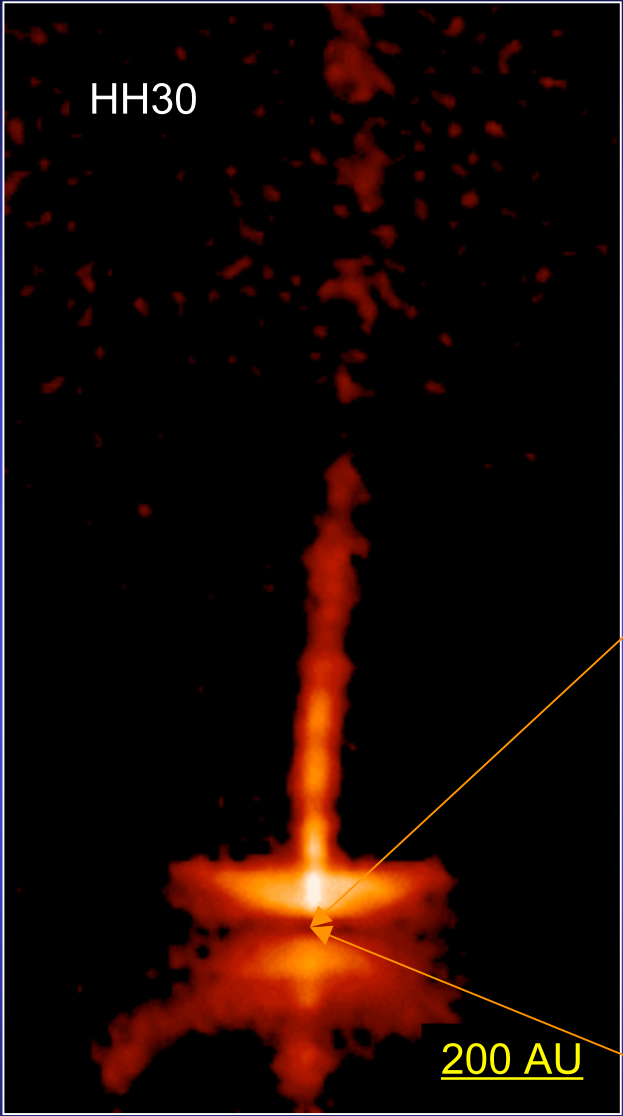
Low-mass stars: Ubiquity -and diversity- of jets and circumstellar disks

The "accretion-ejection" phenomenon and the role of the (molecular) environment





HST

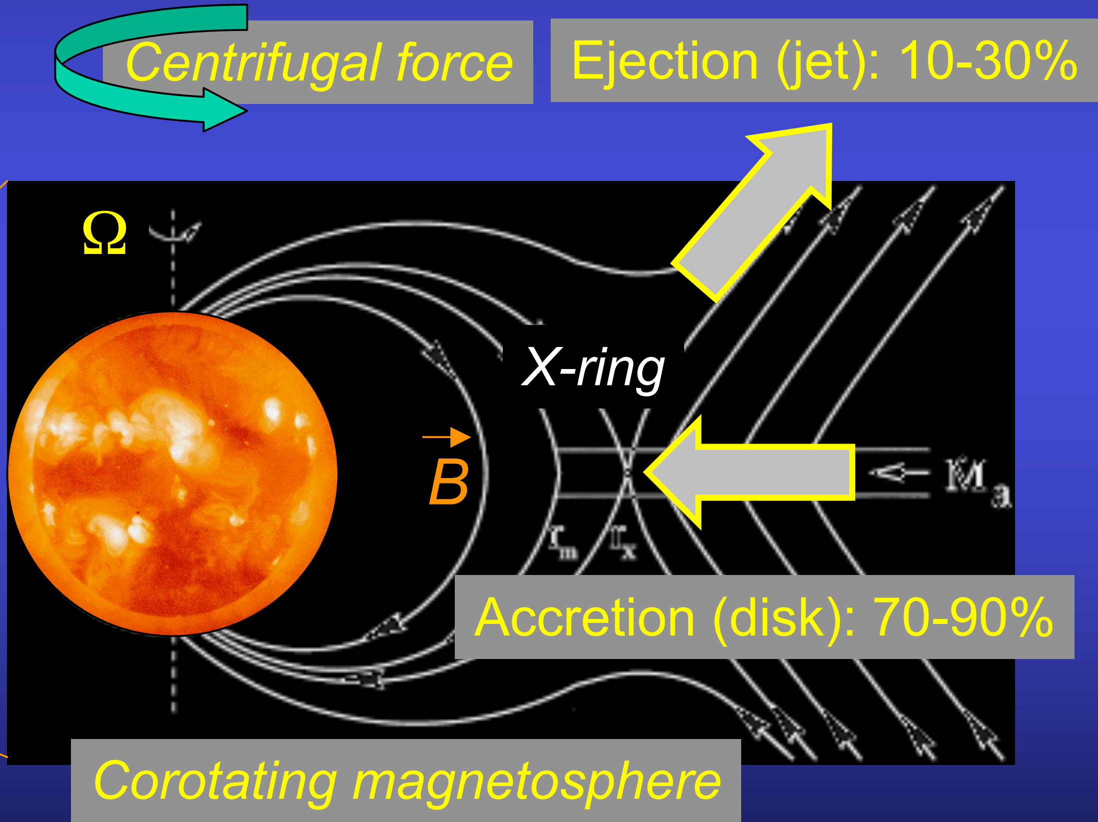


Necessity of magnetic fields:

MHD models for star-disk magnetic coupling

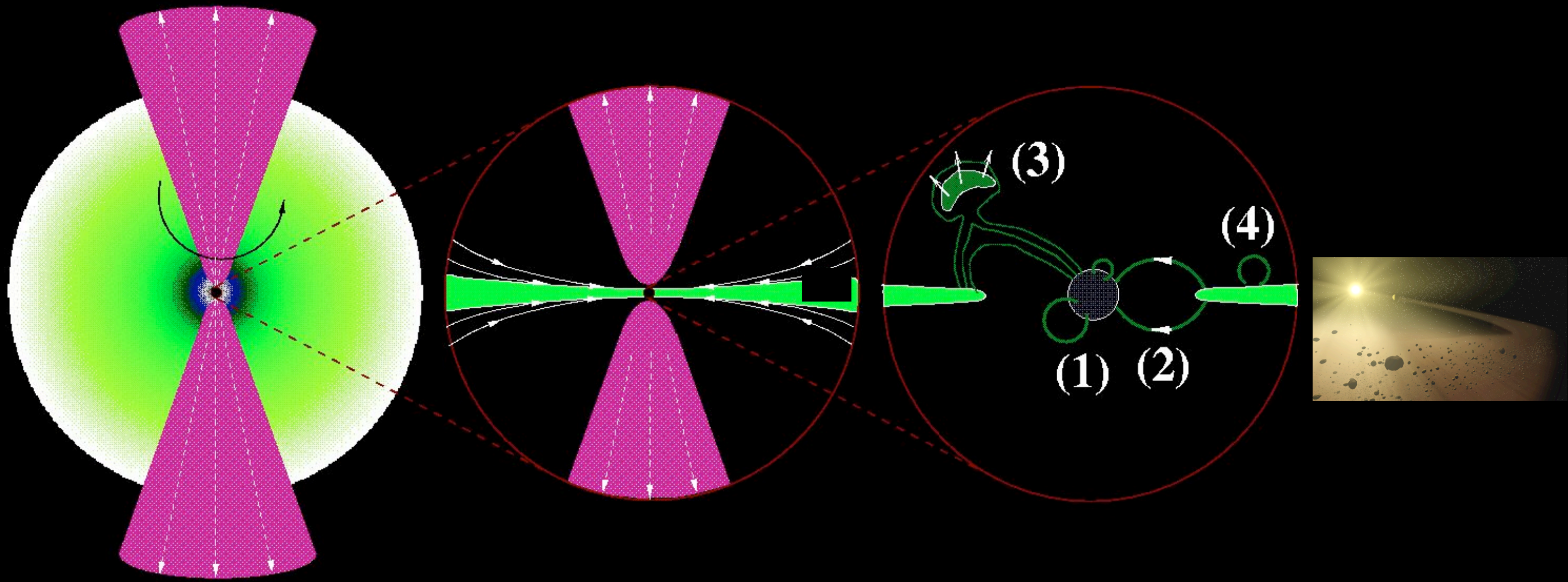
(J. Ferreira et al., 2001, …)

(Shu et al., Pudritz et al., Heyvaerts et al.,…)



YSO magnetic fields ↔ AGN black holes !

A brief history of early low-mass star evolution



10000 AU — 200 AU — 0.5 AU

$10^{4\text{-}5}$ yrs — $10^{5\text{-}6}$ yrs — $10^{6\text{-}7}$ yrs

protostars — *T Tauri stars*

Circumstellar matter

PROPERTIES	*Infalling Protostar*	*Evolved Protostar*	*Classical T Tauri Star*	*Weak-lined T Tauri Star*	*Main Sequence Star*
SKETCH					
AGE (YEARS)	10^4	10^5	$10^6 - 10^7$	$10^6 - 10^7$	$> 10^7$
mm/INFRARED CLASS	Class 0	Class I	Class II	Class III	(Class III)
DISK	Yes	Thick	Thick	Thin or Non-existent	Possible Planetary System
X-RAY	?	Yes	Strong	Strong	Weak
THERMAL RADIO	Yes	Yes	Yes	No	No
NON-THERMAL RADIO	No	Yes	No ?	Yes	Yes

Reconnection + Irradiation effects

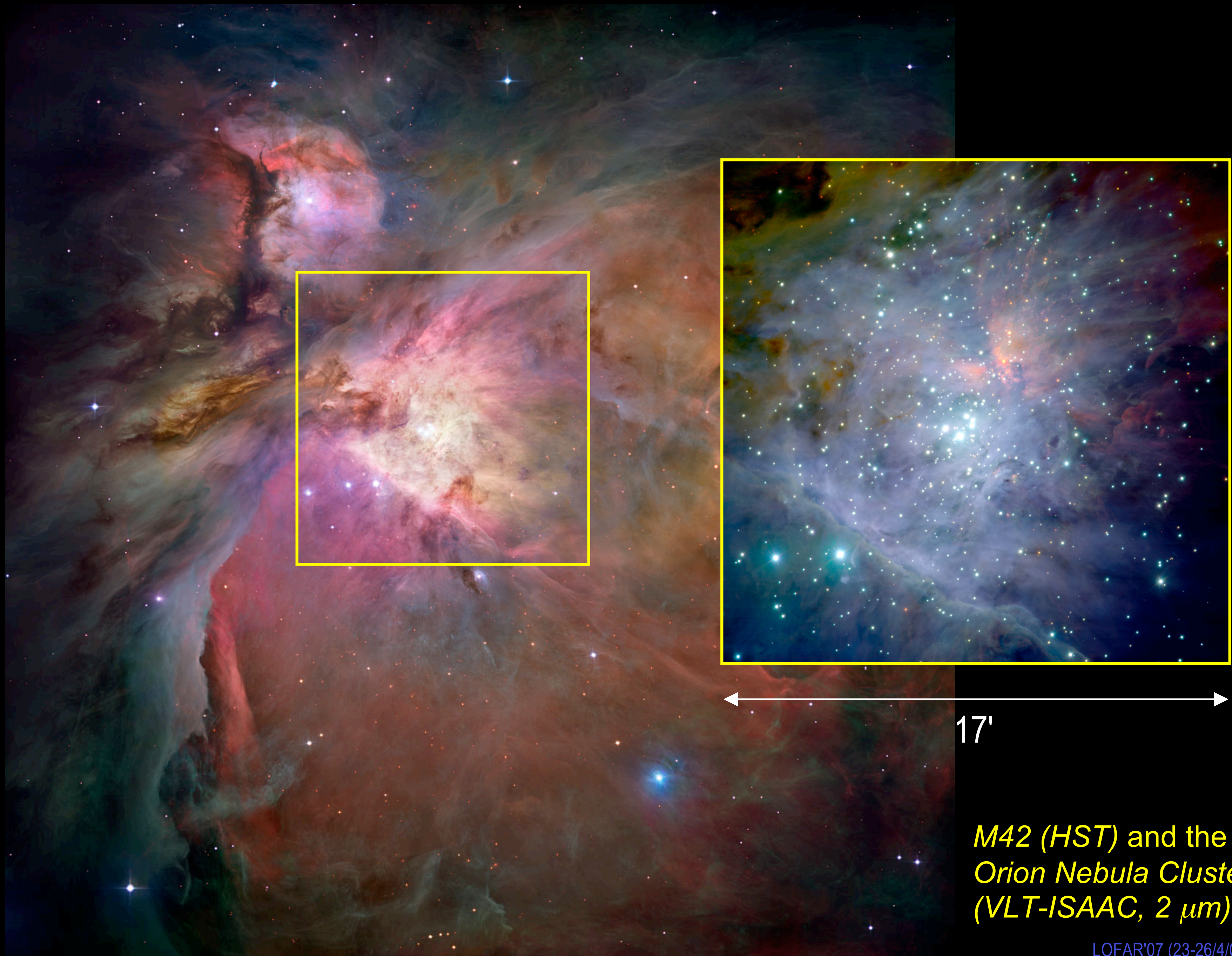
Figure 1 The stages of low-mass young stellar evolution. This review chiefly addresses the bottom three rows of the chart. (Adapted from Carkner 1998.)

2.1 Direct and indirect evidence for magnetic fields: low-mass stars

- X-ray emission
  - Hundreds known !
  - Solar-type activity, enhanced (Sun x 10^{3-4})
  - Frequent luminous flares (≈ 1/day vs 1/yr)
  - "coronal" plasma temperatures (T_X ~ 1-10 MK)
  - "coronal" densities ($n_e \sim 10^{10-12}$ cm^{-3})

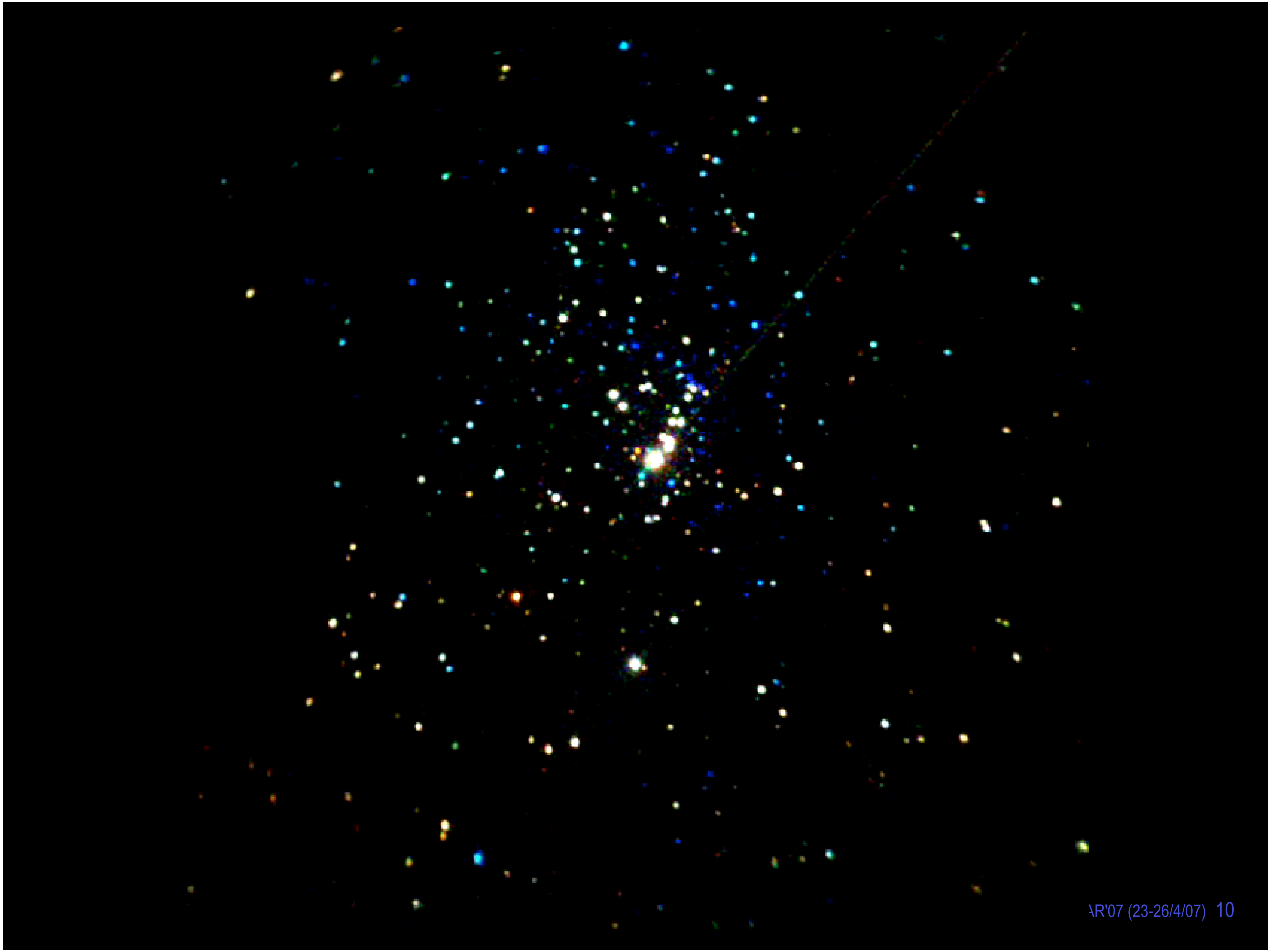
- "Solar paradigm": *plasma confinement by magnetic loops*
  - $L \sim 0.1\ R_* \ (\sim 0.3\ R_\Theta) \rightarrow \sim 3\ R_* \ (\sim 10\ R_\Theta)$: *large !*
  - $B_{eq} \sim 0.1 - 1$ kG: ~ solar active regions
  - B confirmed by Zeeman measurements (optical-NIR lines)
  - Not necessarily at low latitudes (Doppler imaging)

- Case study: "COUP" (*Chandra Orion Ultradeep Project:* PI E.D. Feigelson)
  - = 2 week-exp. of the Orion Nebula Cluster
  - > 1600 sources

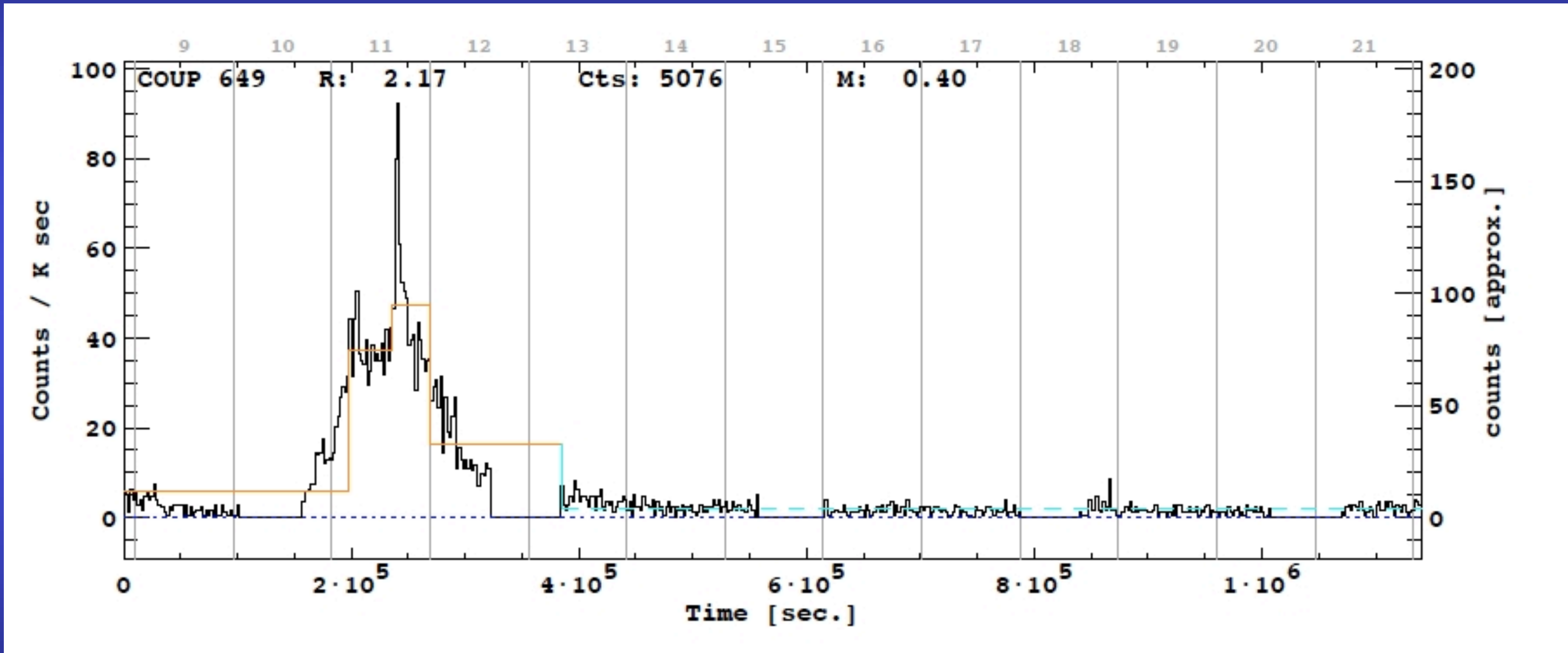


M42 (HST) and the *Orion Nebula Cluster (VLT-ISAAC, 2 μm)*


Chandra X-ray



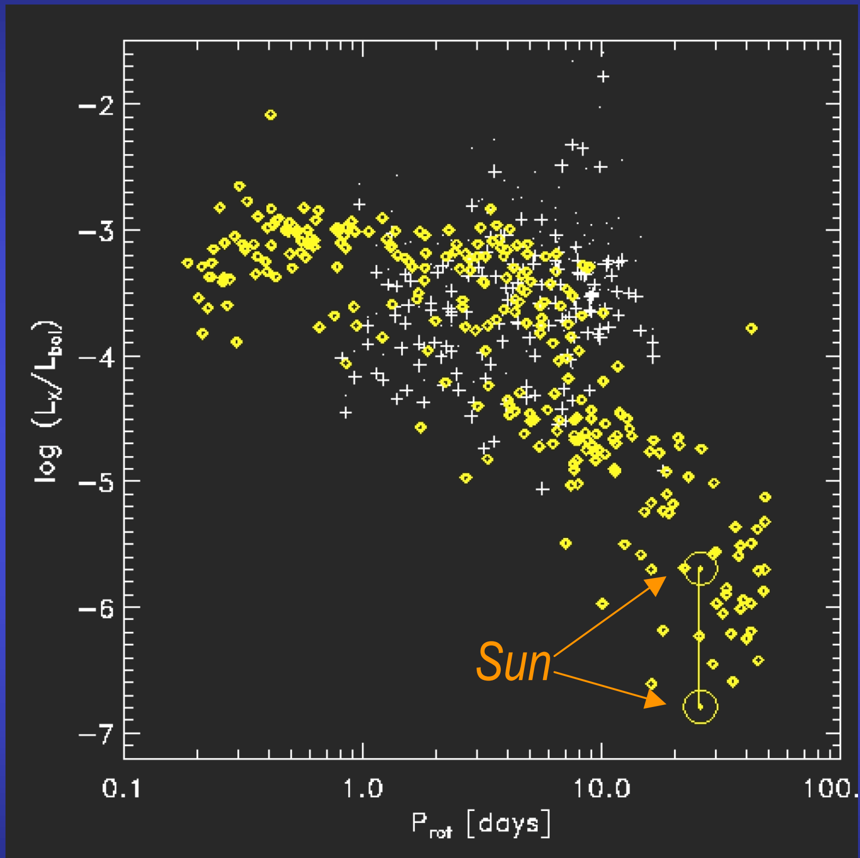
Example: A "monster flare" in a COUP "classical" T Tauri star

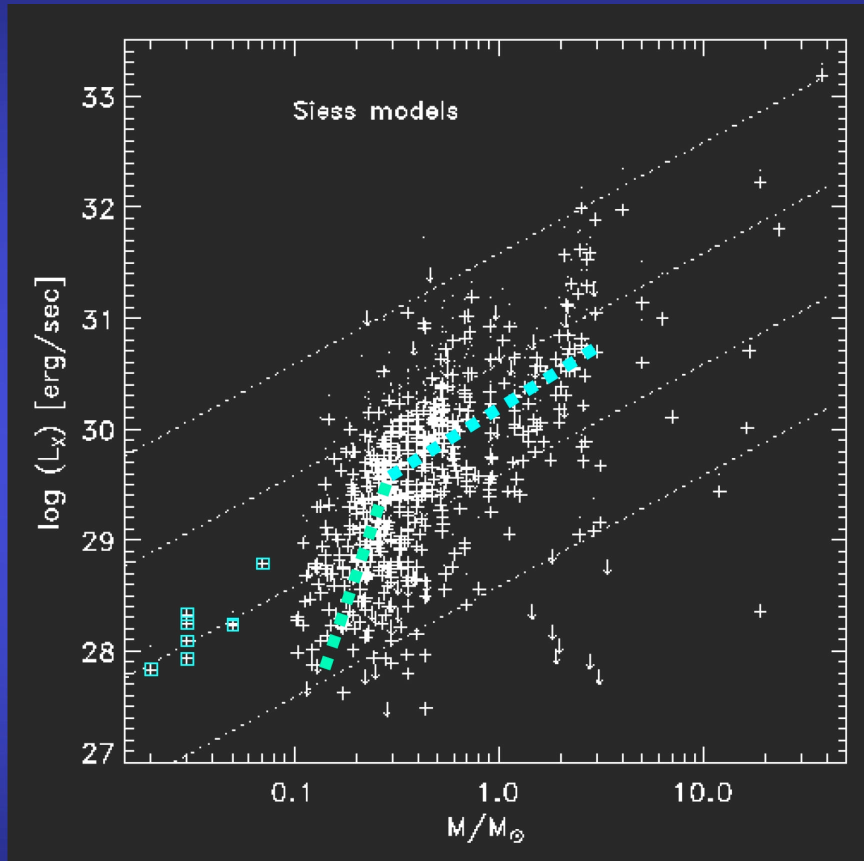


$T_{X,max}$ ~ 100 MK, L >> R_*

(Favata et al. 2005)

COUP: global X-ray properties of the ONC young stars

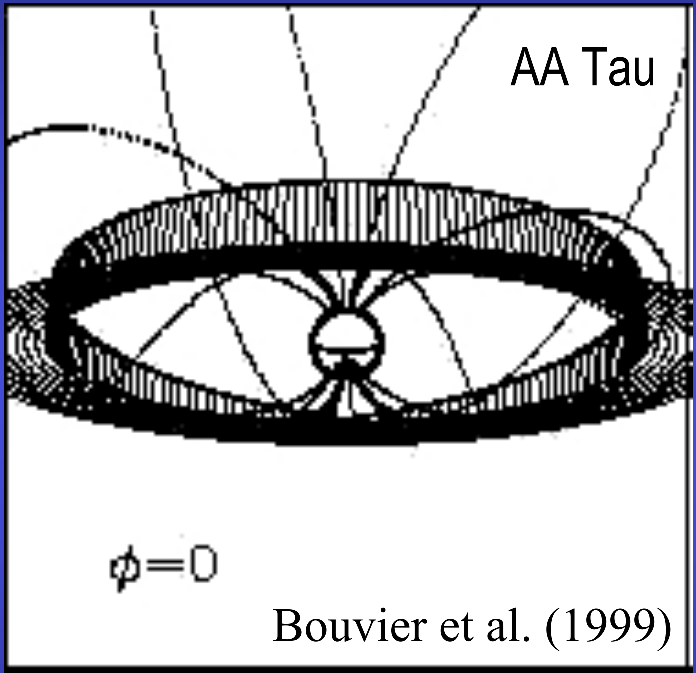




(Preibisch et al. 2005)

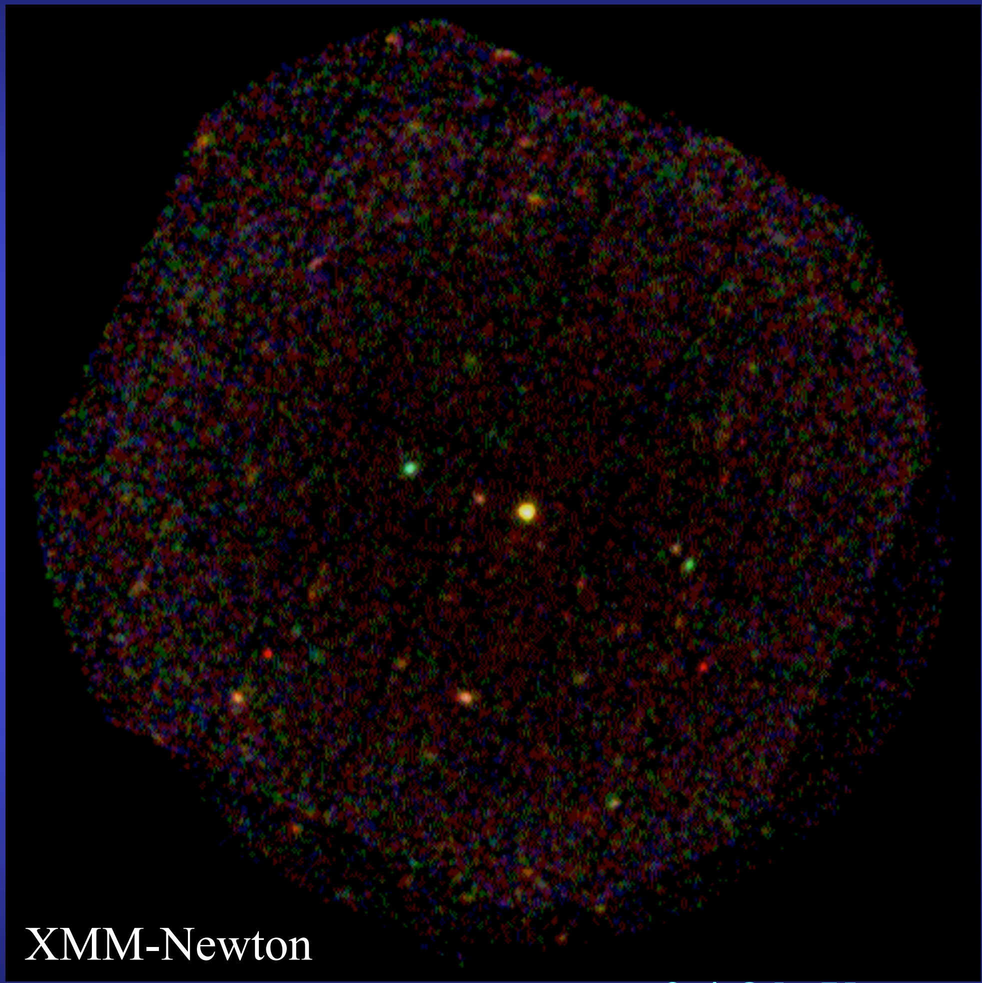
Low-mass stars are fully convective: ω^2 dynamo ?

Steady star-disk interaction: "Magnetospheric accretion":



Magnetospheric accretion model

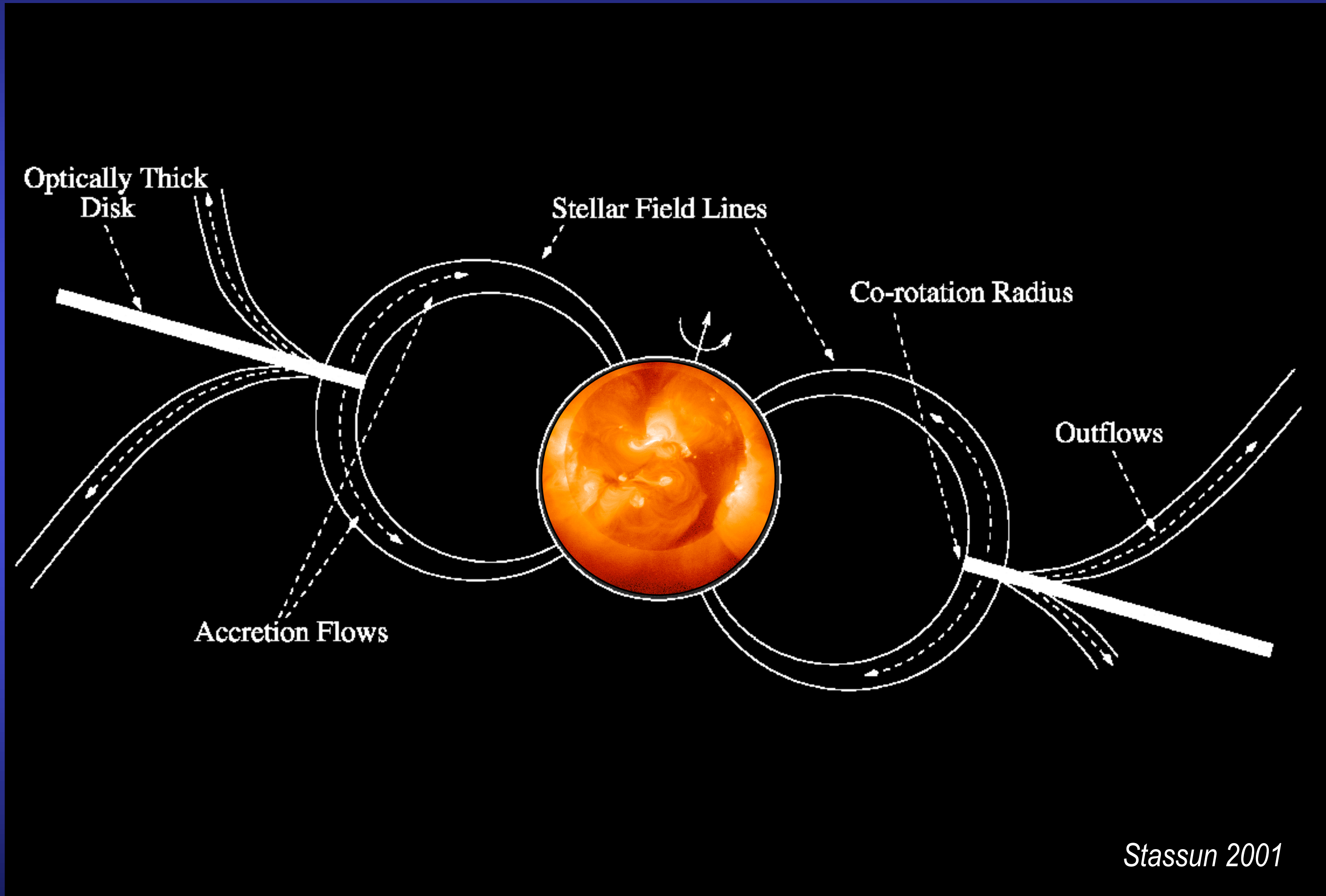
Rotation period ~1 week



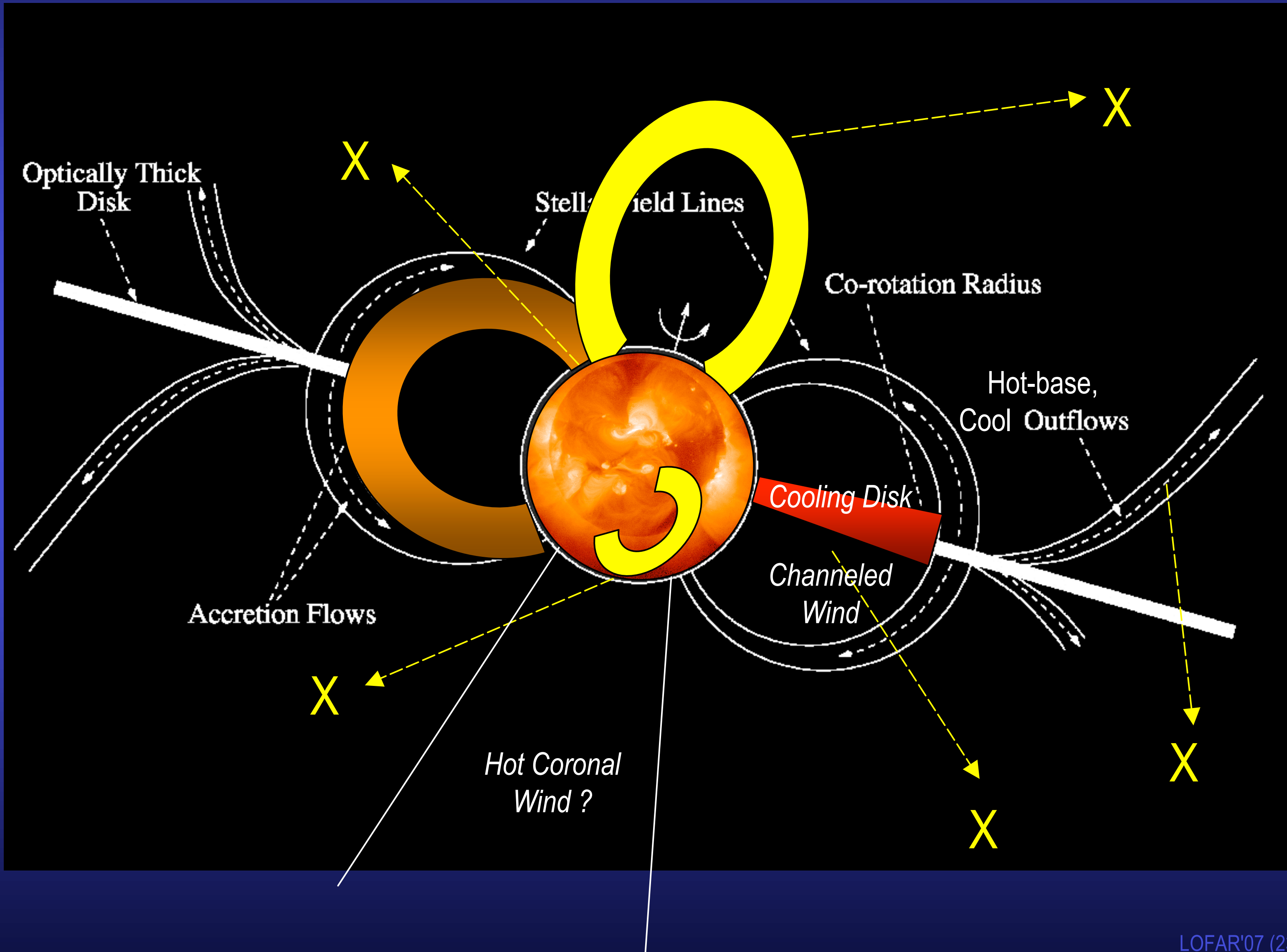
0.5-1 keV **1-2.4 keV** **2.4-8 keV**

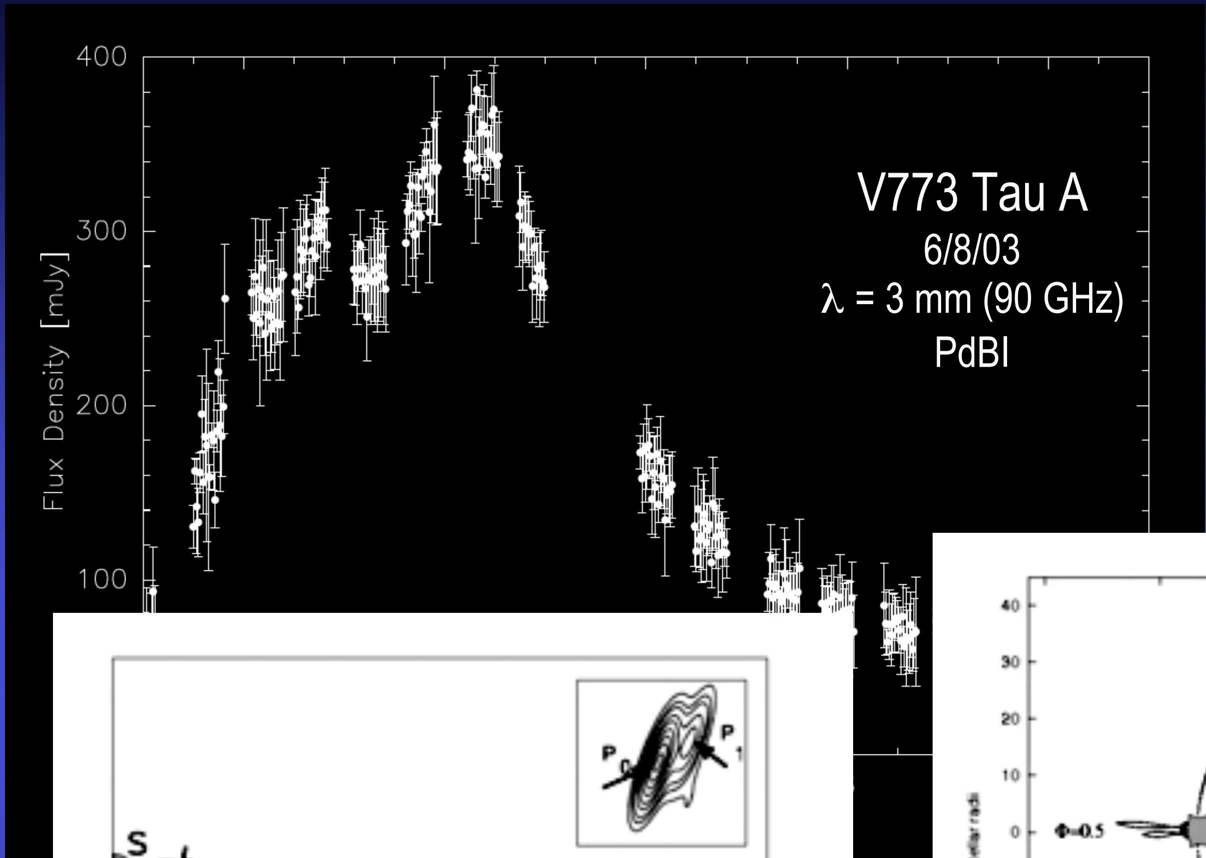
(Bouvier, Grosso, Montmerle et al., in prep.)

The magnetic structure of a "classical" (= accreting) T Tauri star

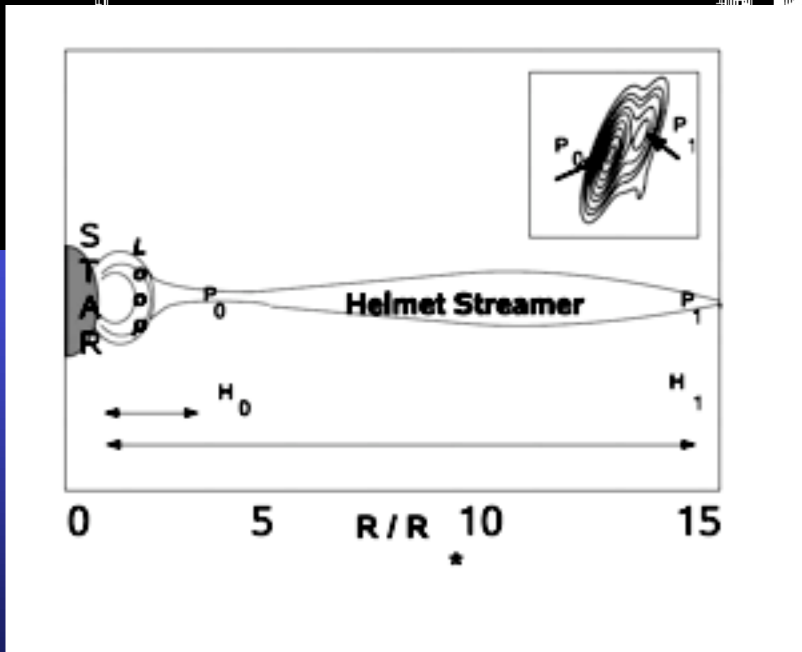


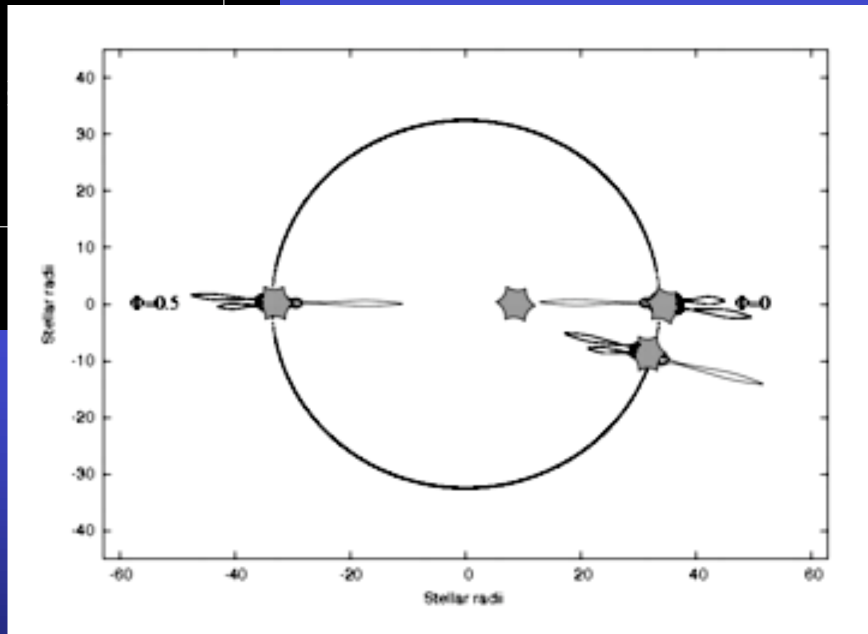
A complex accretion-ejection configuration...





Radio flare from the binary WTTS V773 Tau (P=51 d): *~~Gyro~~-synchrotron*





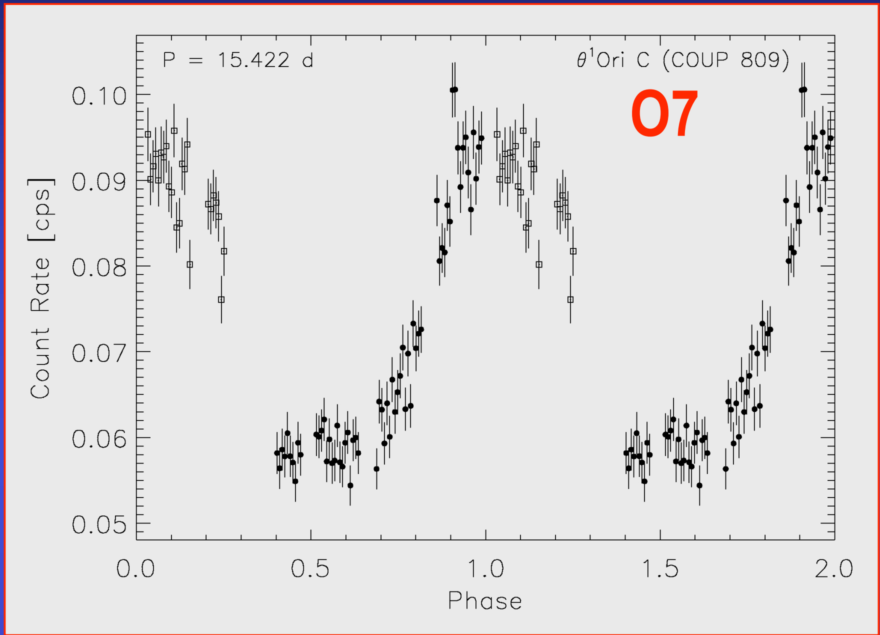
(Massi et al. 2006)

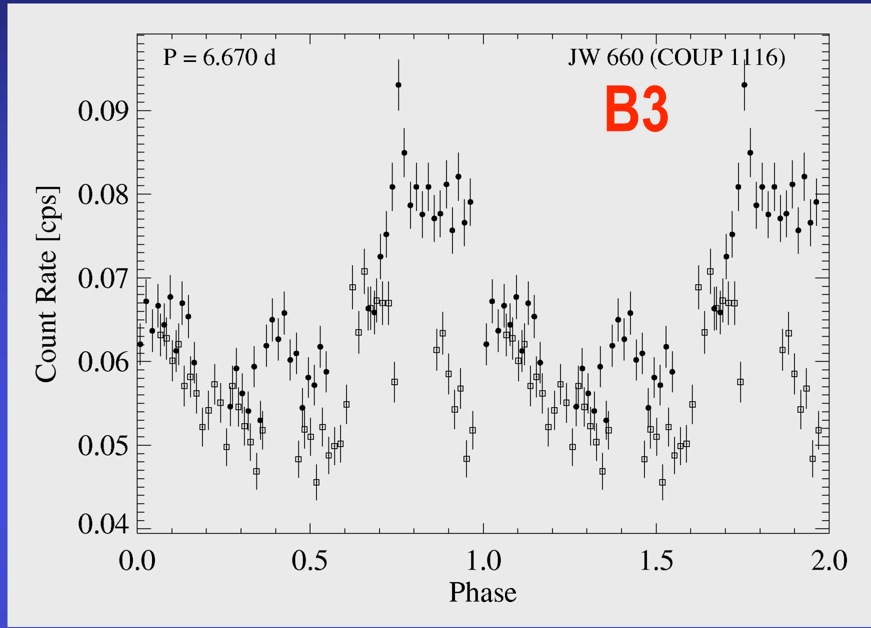
2.2 Direct and indirect evidence for magnetic fields: massive stars

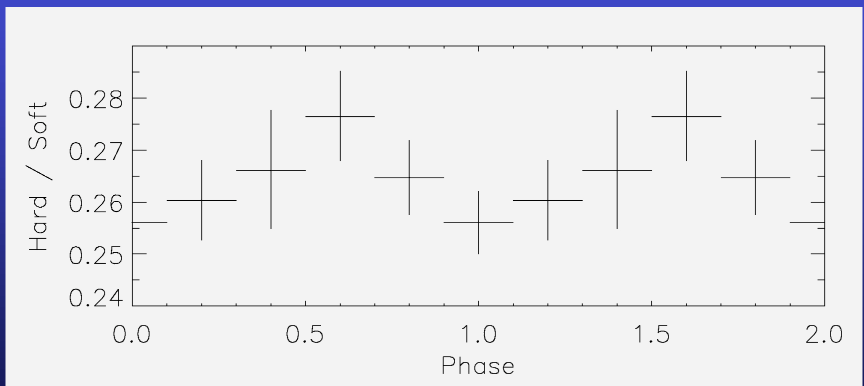
- X-ray emission
  - Usual mechanism: shocks in winds (radiative instabilities)
  - Exotic mechanism if stars are magnetized
    - When $B^2/8\pi > \rho v_w^2$: (dipolar) magnetic field lines are able to confine the wind flow
    - => "Magnetically Channeled Wind Shock Model" (Babel & Montmerle 1997)
    - Opposite shocks from both hemi-magnetospheres
    - COUP evidence(OB stars): rotational modulation (= absorption by cooling disk)

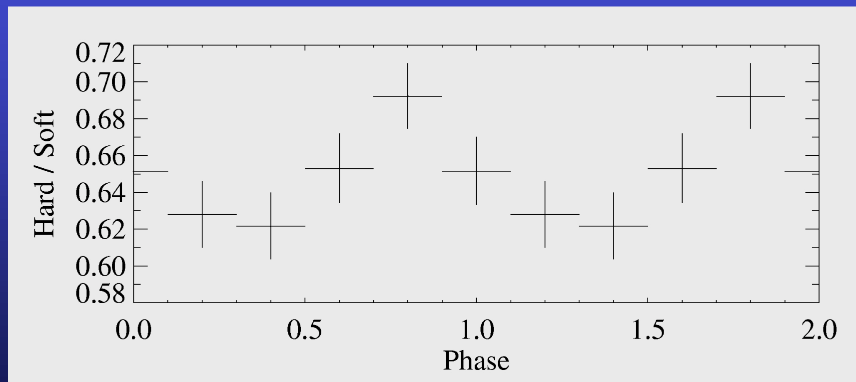
- Radio emission of "magnetic stars" ("CP" = chemically peculiar)
  - Rotational modulation as well (opacity effect)

O-early B stars in Orion:
Week-long periodic X-ray rotational modulation



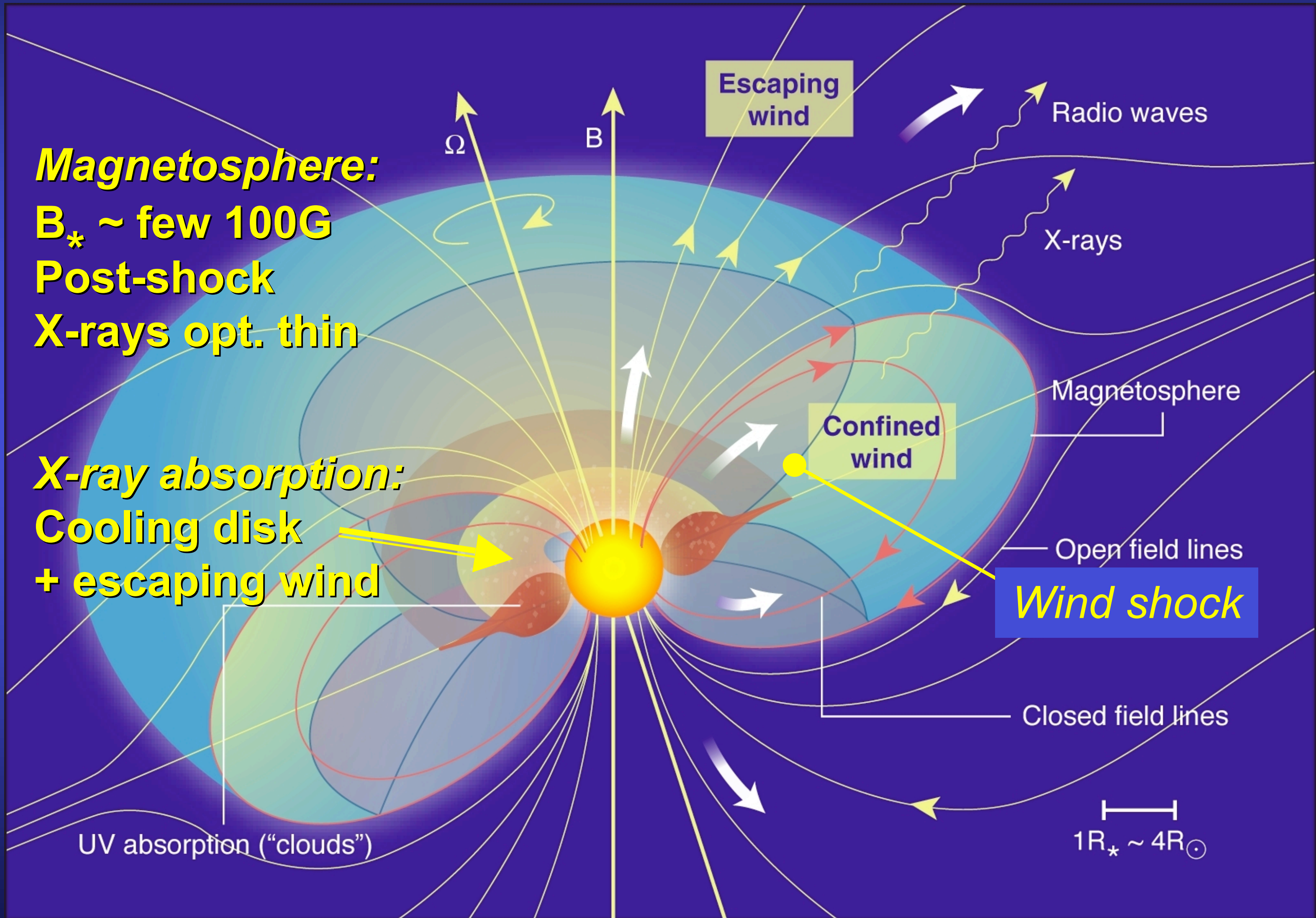






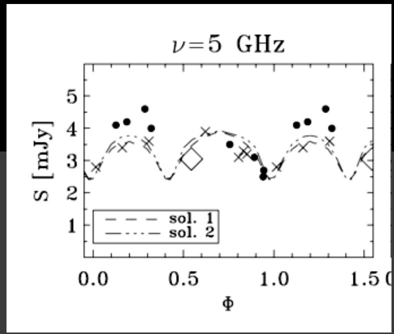
COUP: Stelzer, Flaccomio, Montmerle et al. 2005

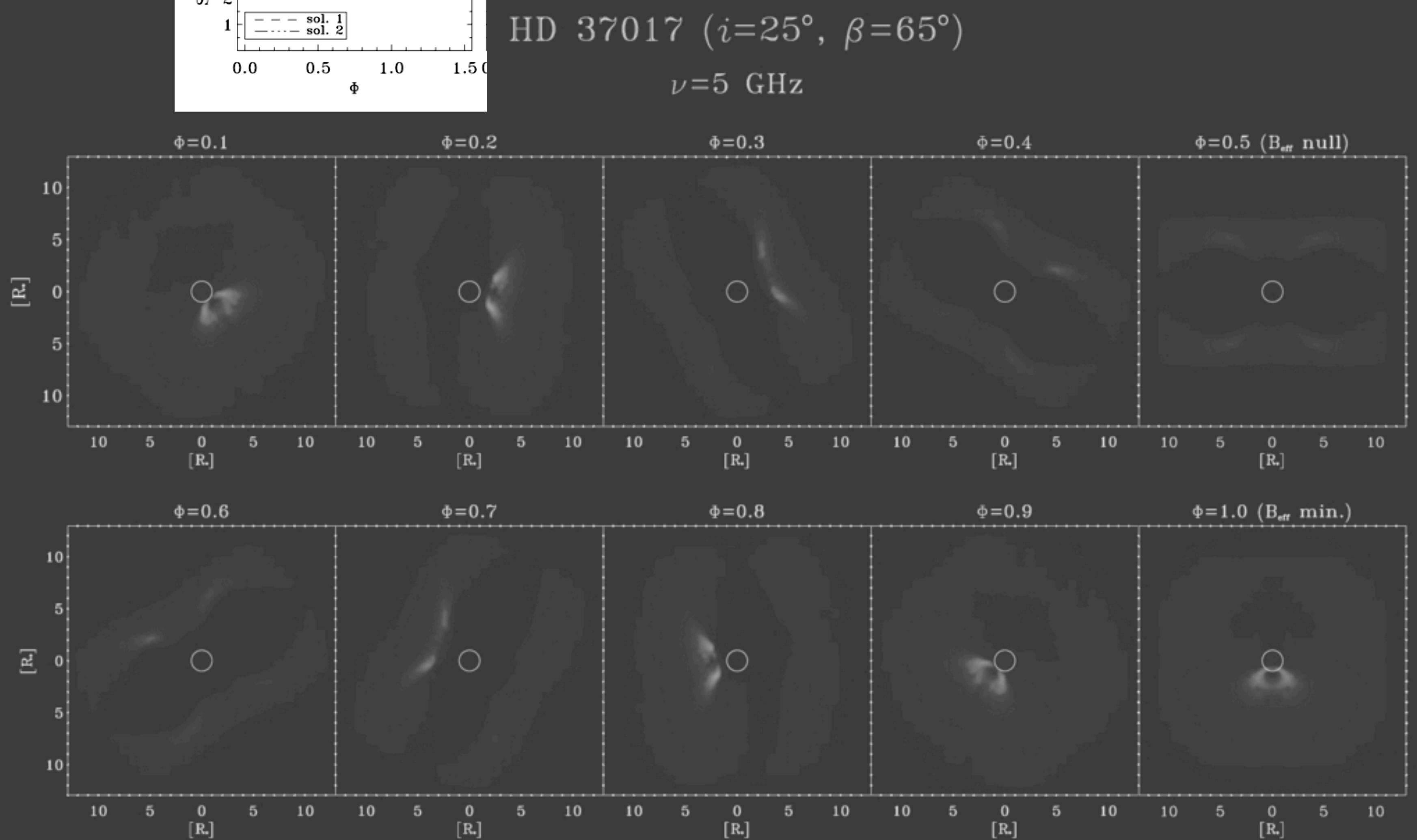
*The **Magnetically Channeled Wind Shock** (MCWS) model*



Montmerle 2001, Science *(after Babel & Montmerle 1997)*

Periodic radio emission from a Bp star:
A rotating, large, wind-confining magnetosphere





(Trigilio et al. 2006)

3. Summary and conclusions

- *Magnetic fields play a central role* in low-mass young stars, as well as in a fraction of massive stars
- *They are the "central engine"* for the accretion-ejection phenomenon
- *Flaring activity* (i.e., magnetic reconnections) is widespread
- Magnetic structures are often *very large* (up to 10 R_* ~ 0.01 AU)
- They can connect the star and the disk, or two stars, even in wide binaries
  - *Periodic variability* is often a signature of large magnetospheres
- LOFAR is able to open a new window on magnetically related processes in young stars, either in *clusters* (statistical approach) or individually (spatially resolved structures: jets)…

Example: *An E-LOFAR survey of the ONC ?*

- mechanisms for LF radio emission
    - evaporating disks
    - jets (hear J. Eislöffel's talk !)
- time variability (min -> weeks):
    - flares, rotational modulation
    - star-disk interactions ?