X-rays from protostars:
the holy grail…

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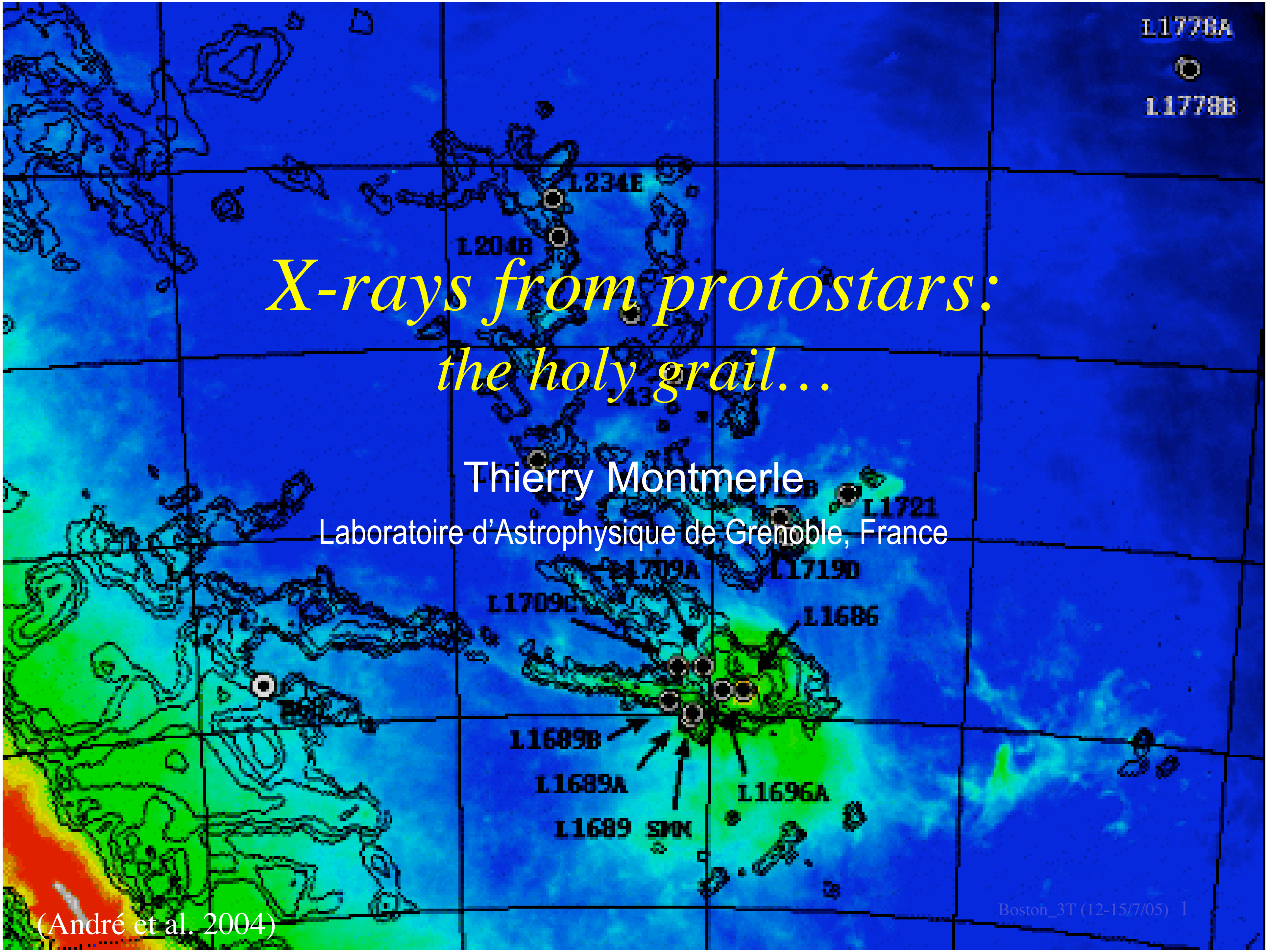


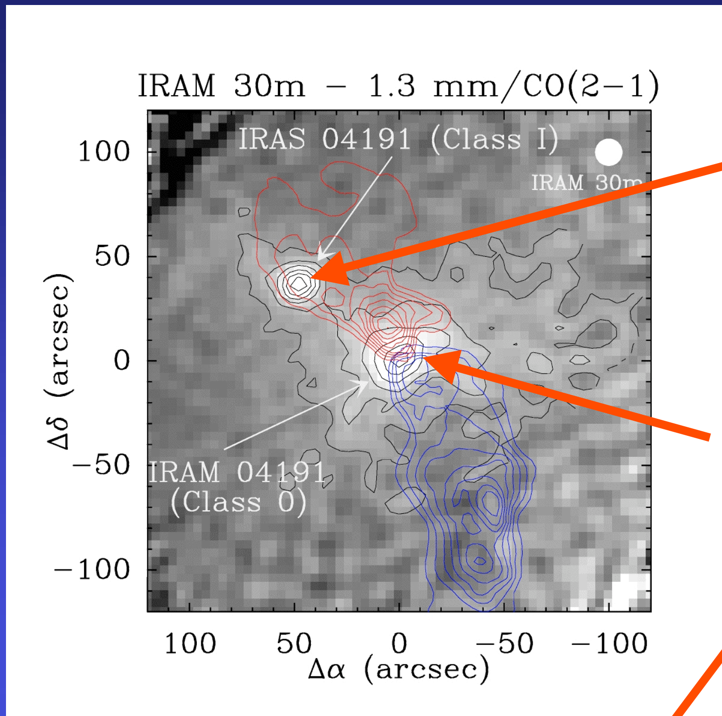
(André et al. 2004)

Outline

- 1. What is a protostar ?
  From gravitational collapse to young T Tauri stars
- 2. Why are X-rays important/essential ?
  Feedback effects on surrounding material
- 3. Results from X-ray observations (1)
  Increasing extinction: From Class II to Class I
- 4. Results from X-ray observations (2)
  From Class I to Class 0
- 5. Conclusions and open issues

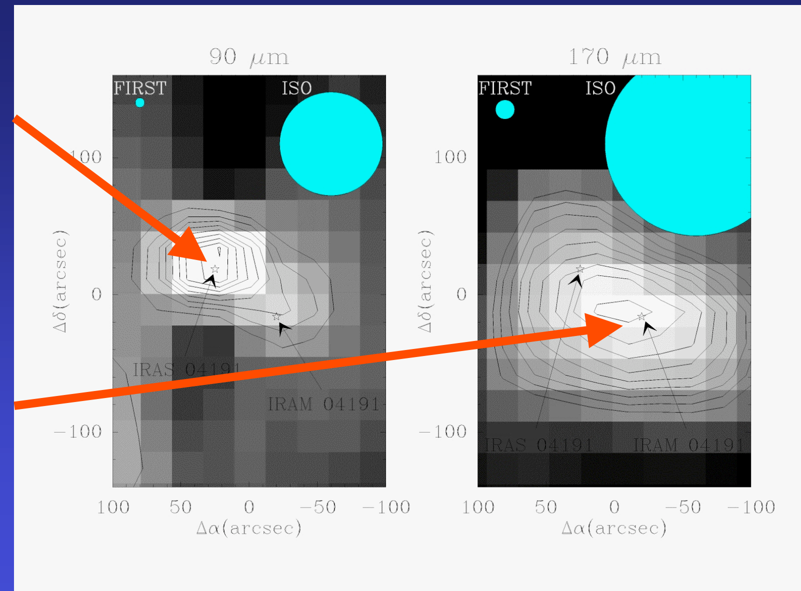
1. What is a protostar ?

- First stage of star formation: collapse of a prestellar core
  - Bonnor-Ebert sphere: see, e.g., B68 (Alves & Lada)
- Central region: "seed" nucleus becoming optically thick.
  - Contraction slows down, surrounding matter "rains" on nucleus (process still debated: inside-out ? Or external collapse ? May depend on external conditions)
- An outflow develops, the central nucleus becomes hot enough to emit cm radiation
  - => jet + disk ?
- Observationally:
  - cold (10-20 K => mm) extended envelope + outflow + hot (cm -> VLA) source; envelope optically thick (even mm: A_V > few 100)
    - => "Class 0" protostar; phase ~ 10^4 yrs
  - As a result of accretion, envelope becomes optically thin to mm and IR, revealing central object => IR source;
    - => "Class I" protostar, phase ~ 10^5 yrs

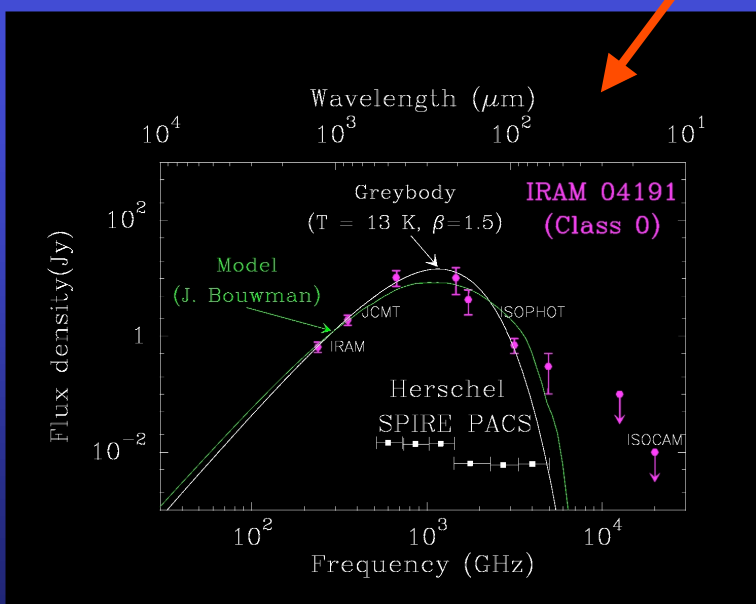


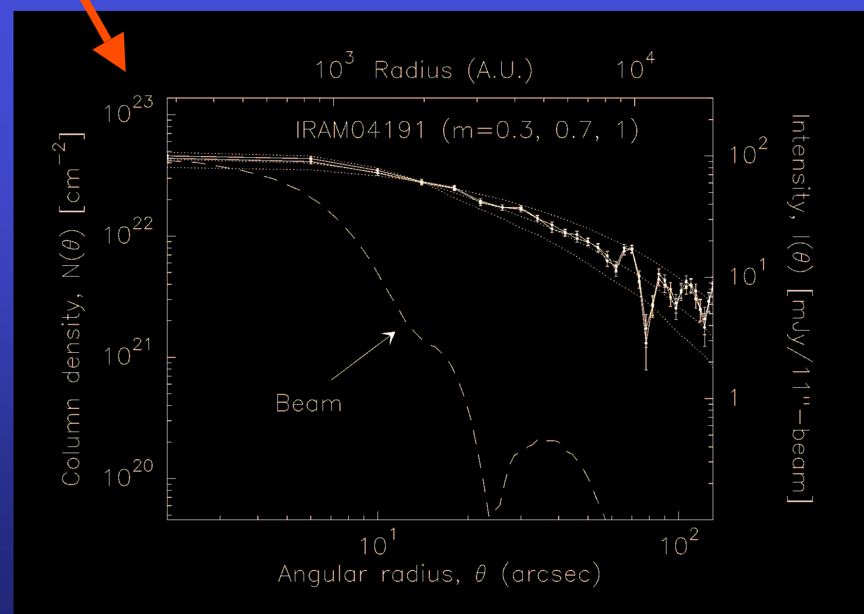
IRAS 04191 (low-mass Class I)

IRAM 04191 (low-mass Class 0)



(André et al. 2000)

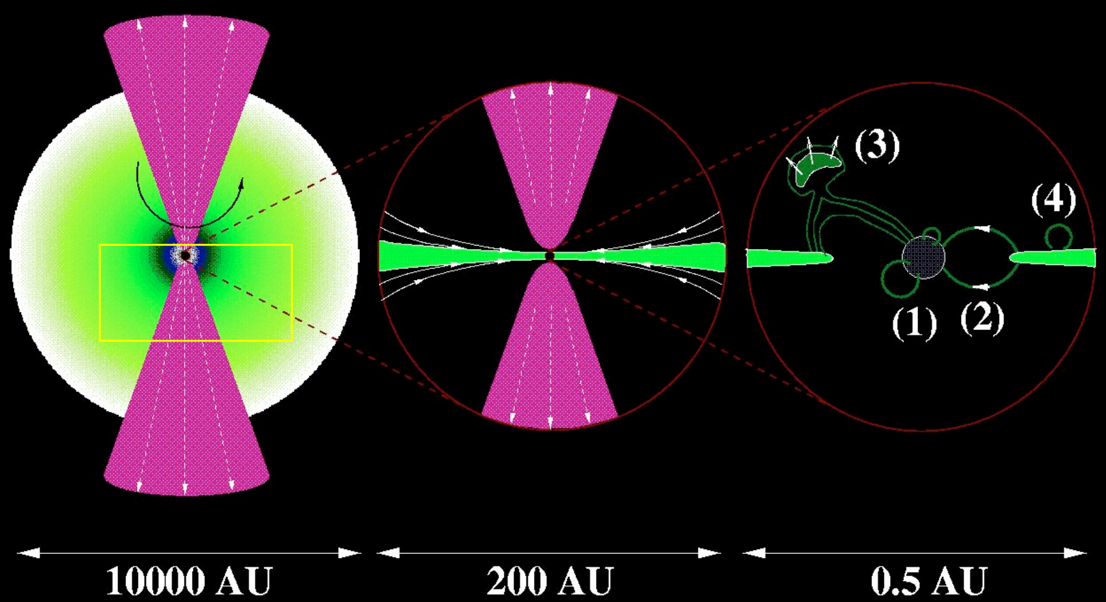




Continuous evolution *from collapsing protostars to strongly accreting, young T Tauri stars;*

Accretion/ejection **<=> dominant role of magnetic fields**

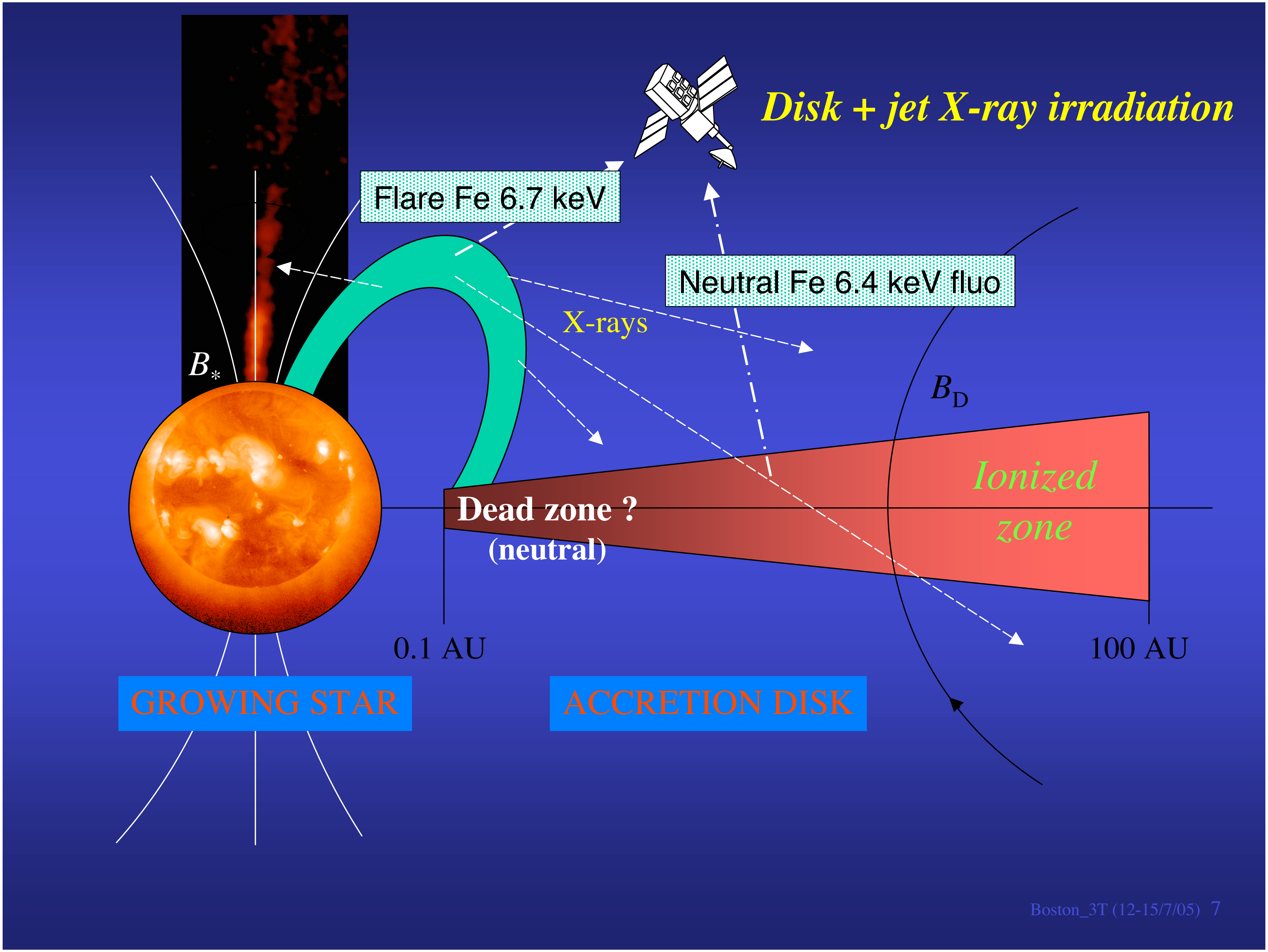
Class 0 → I   Class I → II



~ 10^4 yrs → ~ 10^5 yrs → ~ 10^6 yrs

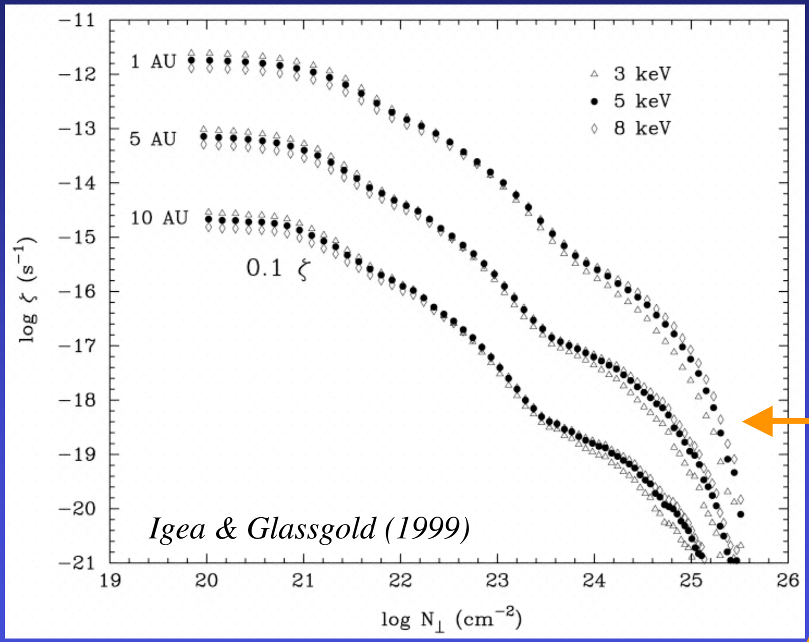
2. Why are X-rays important/essential in protostars ?

- Feedback irradiation effects on surrounding circumstellar material: ionization, heating, fluorescence
  - Effects on chemistry (=> diagnostics) + heating
- Studied theoretically on disks & jets
  - Provides ionization fraction: $x_e = n_e/n_p \sim 10^{-9}$ - 10^{-5}
    - (ISM + LECR => $x_e \approx 10^{-7}$)
  - Effects on cold material: fluorescence (from AGNs)
    - Fe line @ 6.4 keV
- Ionization provides necessary *coupling between circumstellar matter and magnetic fields* via ambipolar diffusion
- This coupling regulates large-scale accretion vs. ejection in an otherwise neutral environment (e.g., Shu et al., Ferreira et al…)



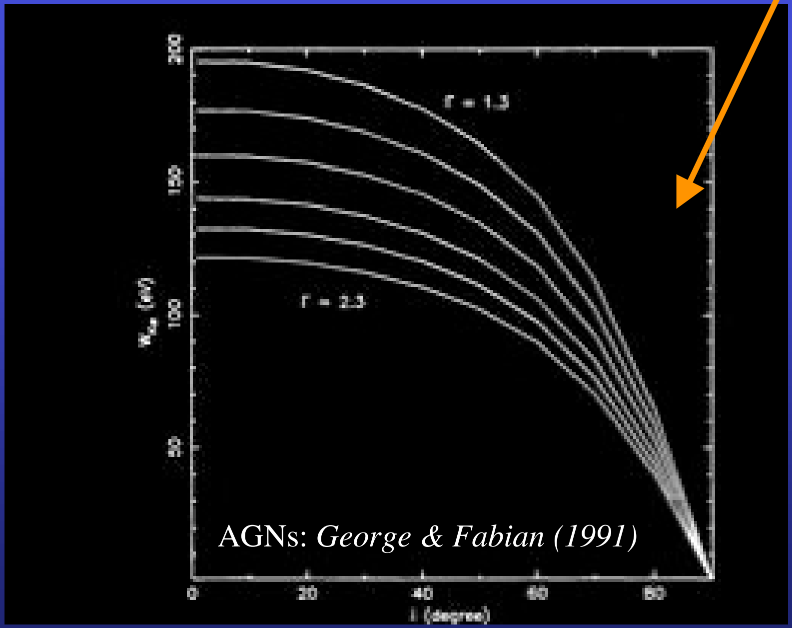
Disk + jet X-ray irradiation
Flare Fe 6.7 keV
Neutral Fe 6.4 keV fluo
X-rays
B_*
B_D
Dead zone ?
(neutral)
Ionized zone
0.1 AU
100 AU
GROWING STAR
ACCRETION DISK

X-ray effects



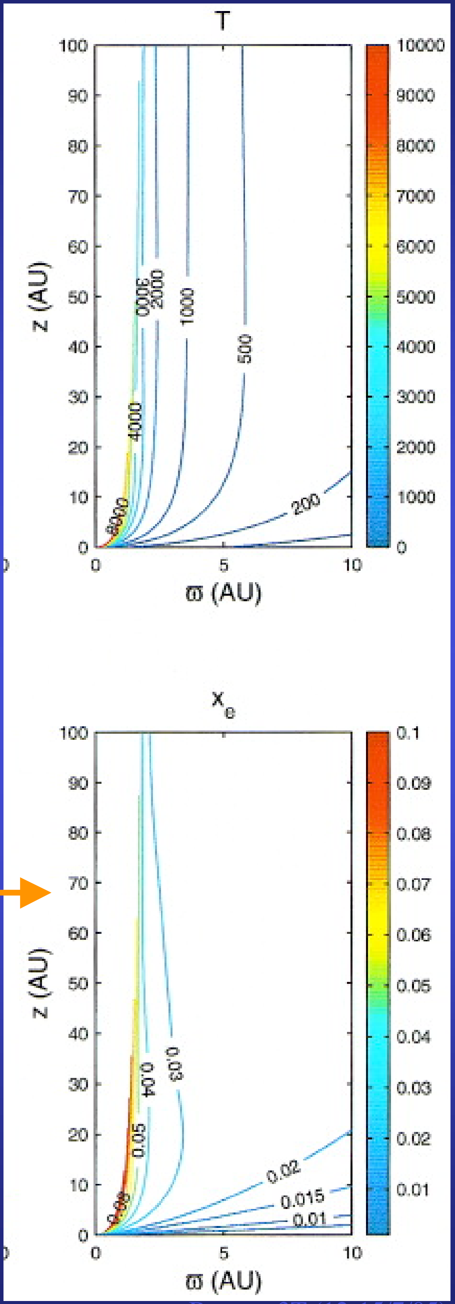
Igea & Glassgold (1999)

On disks:
Ionization + fluorescence



AGNs: *George & Fabian (1991)*

On jets:
Contribution to ionization (also heating…)

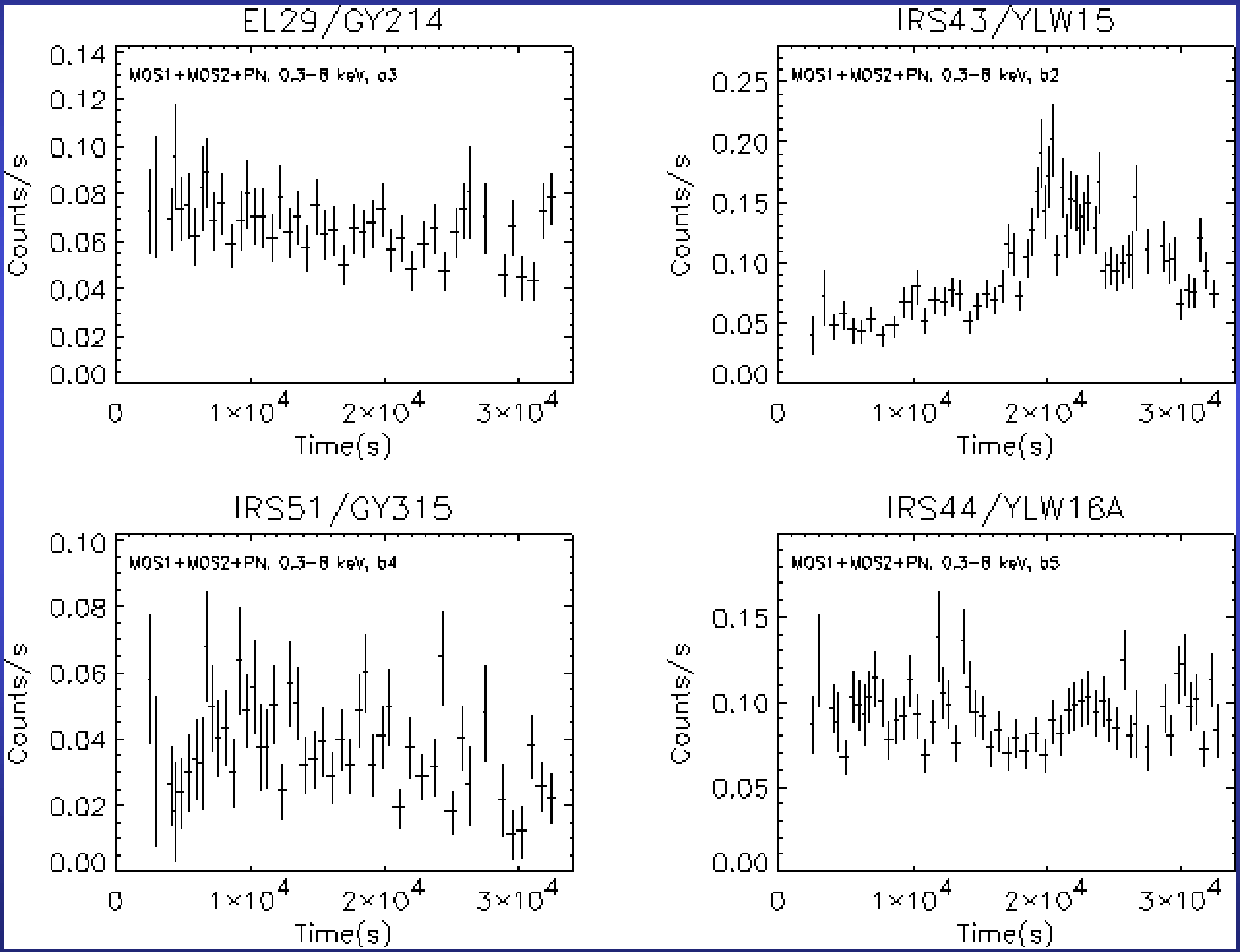


Hsiang et al. (2002)

3. Results from X-ray observations (1)

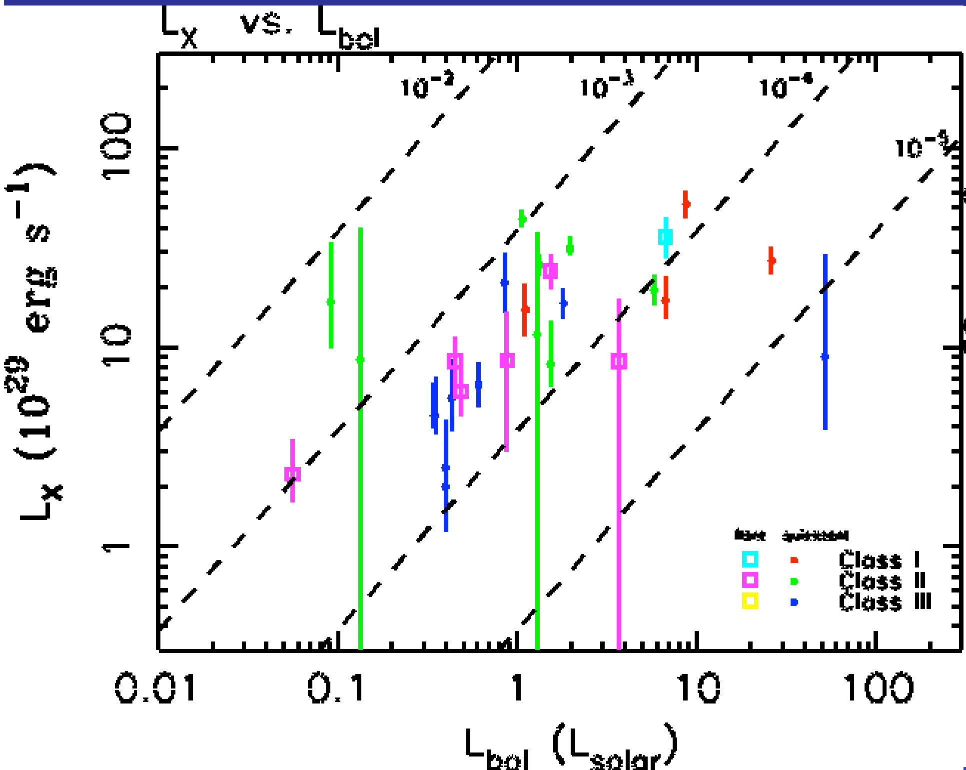
From Class II to Class I

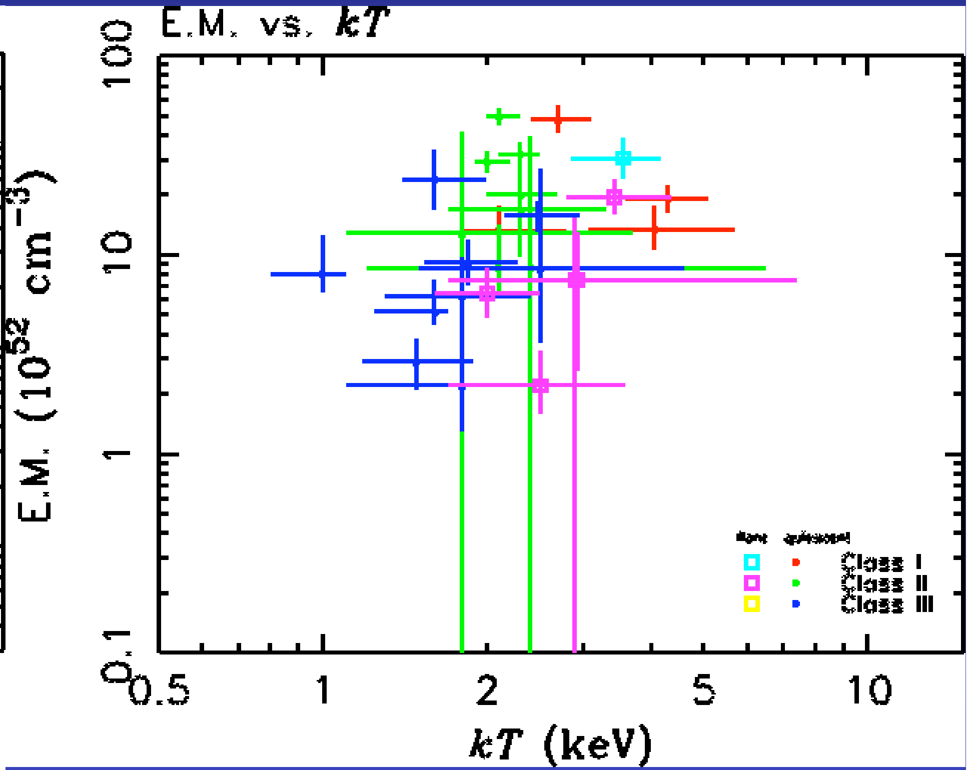
X-ray light curves of Class I protostars in ρ Oph (XMM)



(Ozawa et al. 2005)

X-ray properties, from Class I to Class III: ρ Oph, XMM



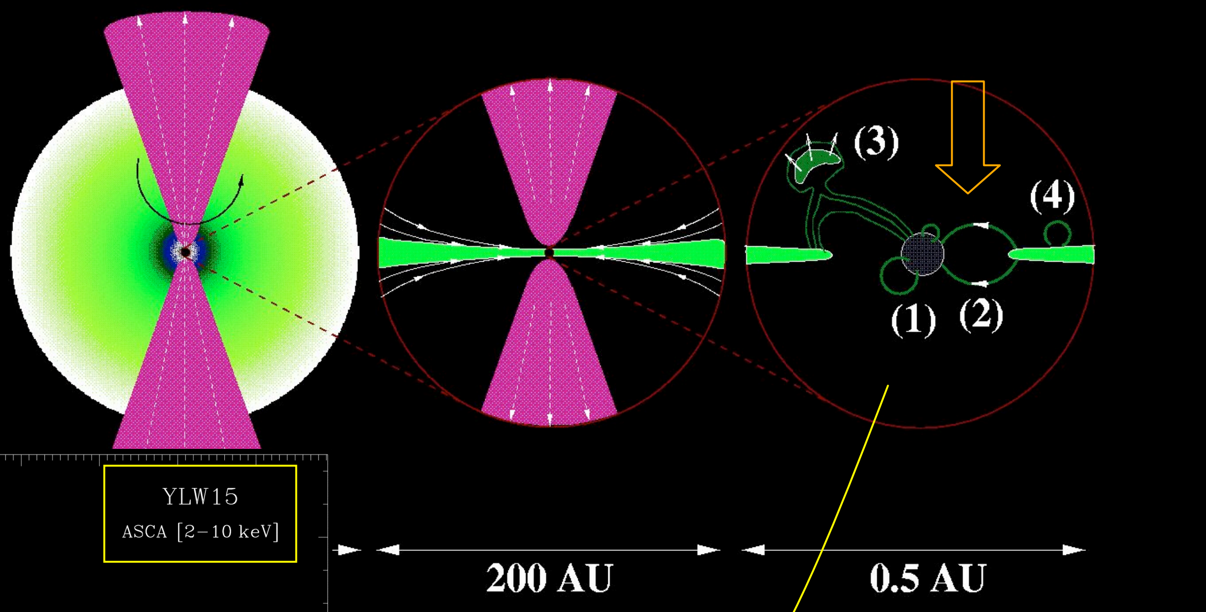


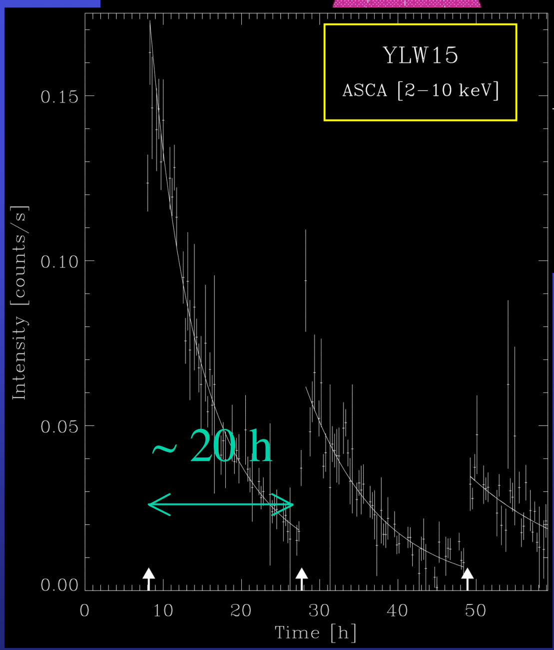
Class	kT (keV)	N_H (10^{22} cm^{-2})	E.M. (10^{52} cm^{-3})
I	2.78 (0.32)	4.52 (0.29)	17.7 (2.4)
II	2.12 (0.15)	1.48 (0.11)	25.5 (2.9)
III	1.41 (0.18)	0.81 (0.11)	4.7 (1.1)

(*Ozawa et al. 2005*)

A triple flare from a Class I protostar : YLW15 in ρ Oph

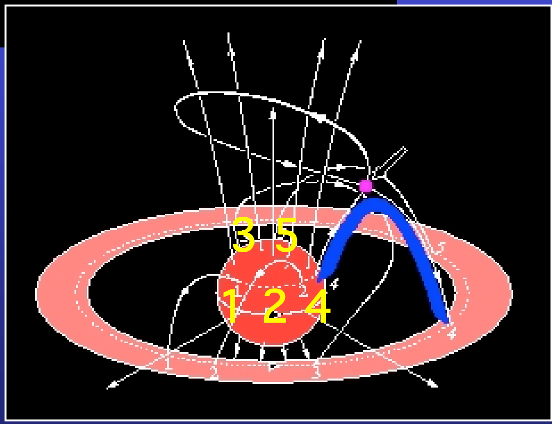
seeing the star-disk central engine ?





Tsuboi et al. 2000

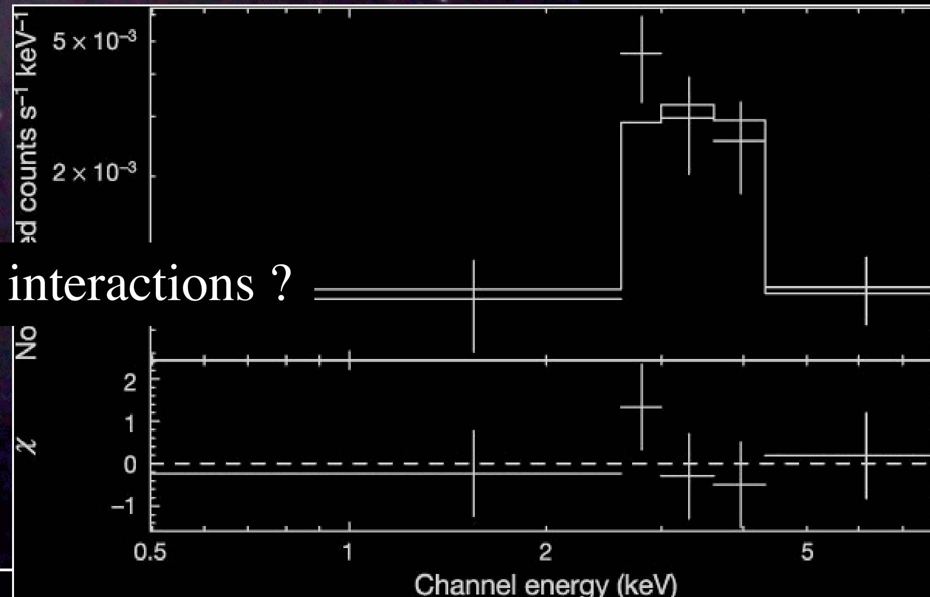
?

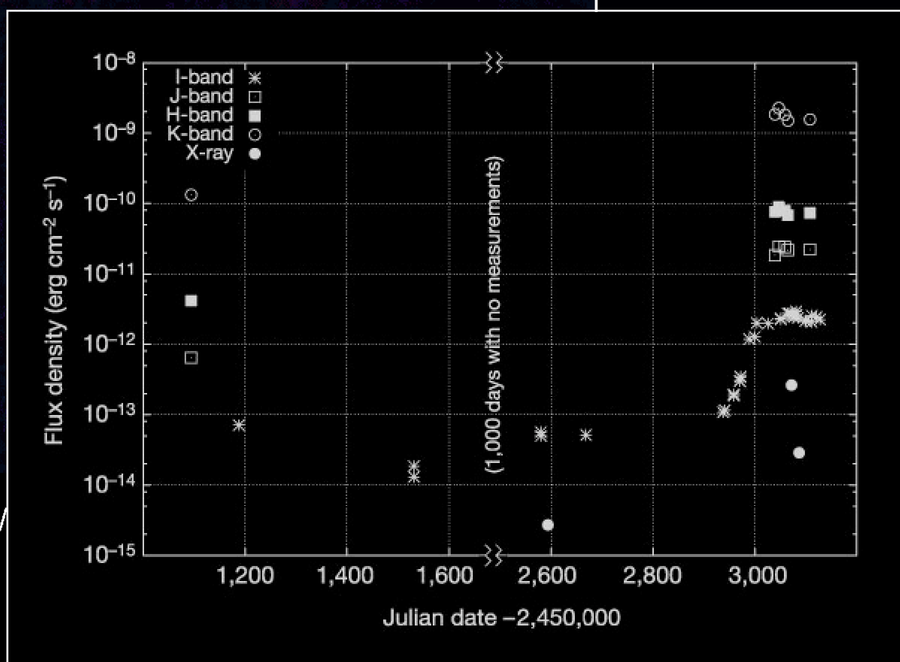


Montmerle et al. 2000

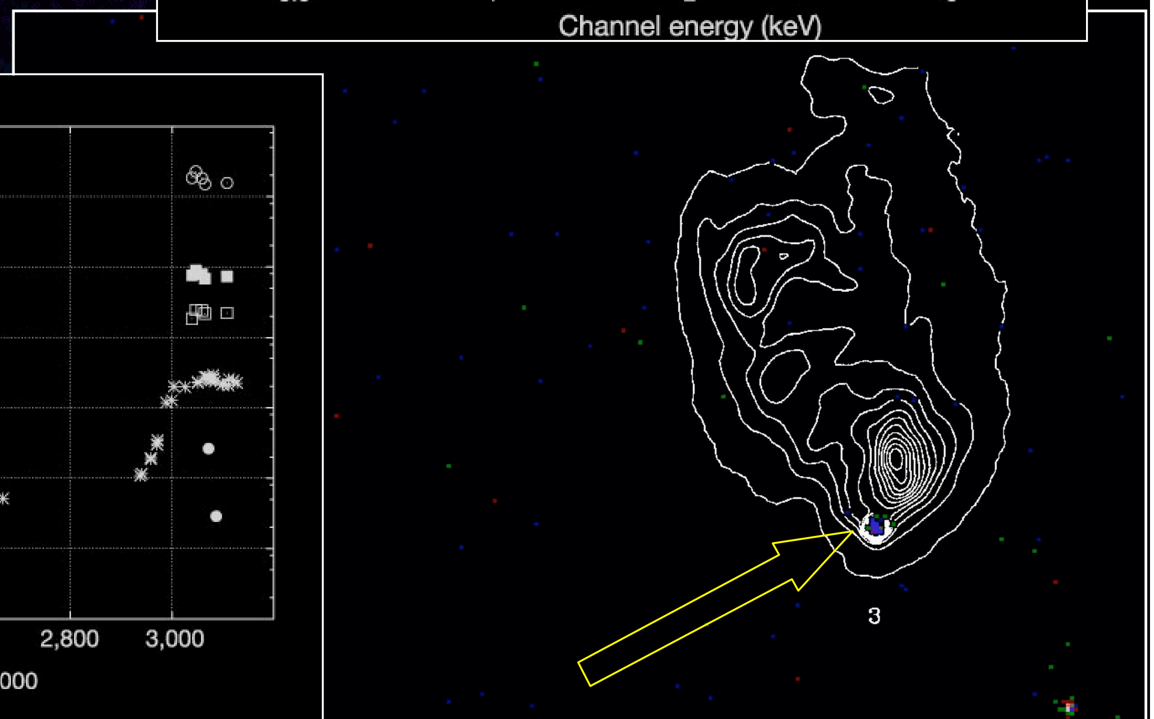
Ourburst of McNeil's nebula in Orion, spring 2004:
EX Ori-type event in Cl. I ?

Very hot gas: evidence for star-disk interactions ?





A. Block/

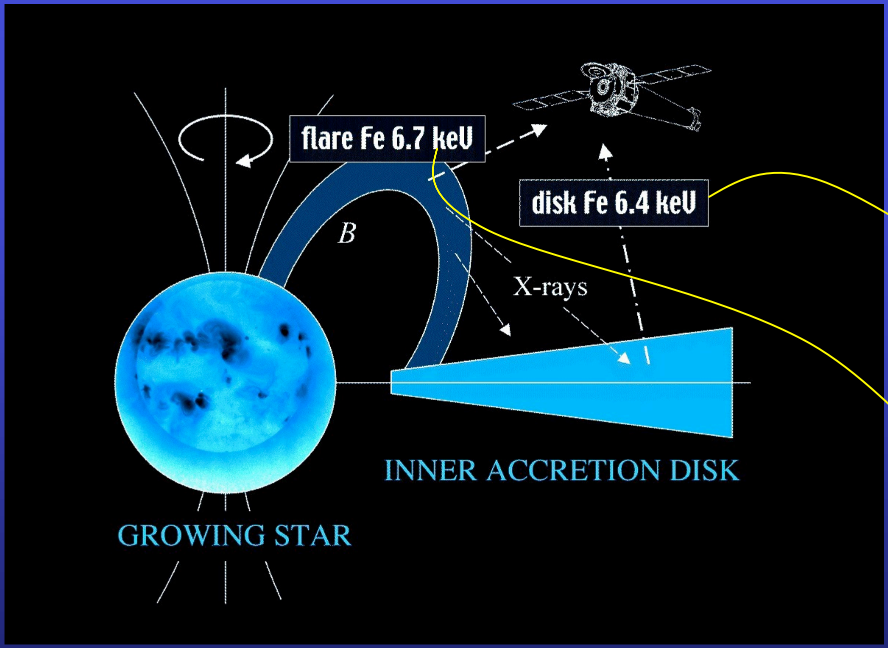


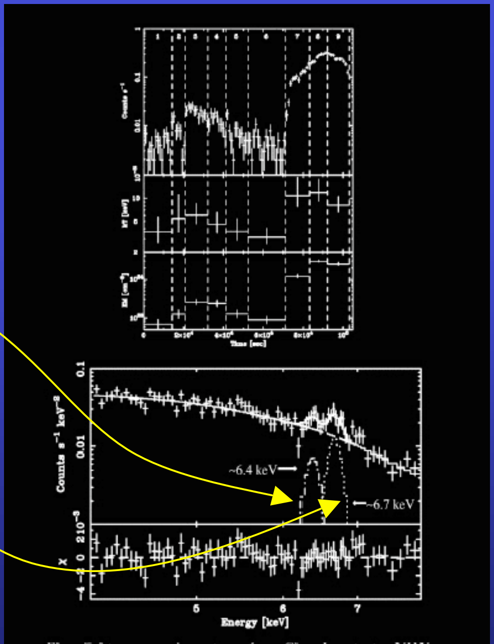
Kastner, J.H., Richmond, M., Grosso, N. et al. 2004, Nature

Disk irradiation: fluorescence

- X-rays

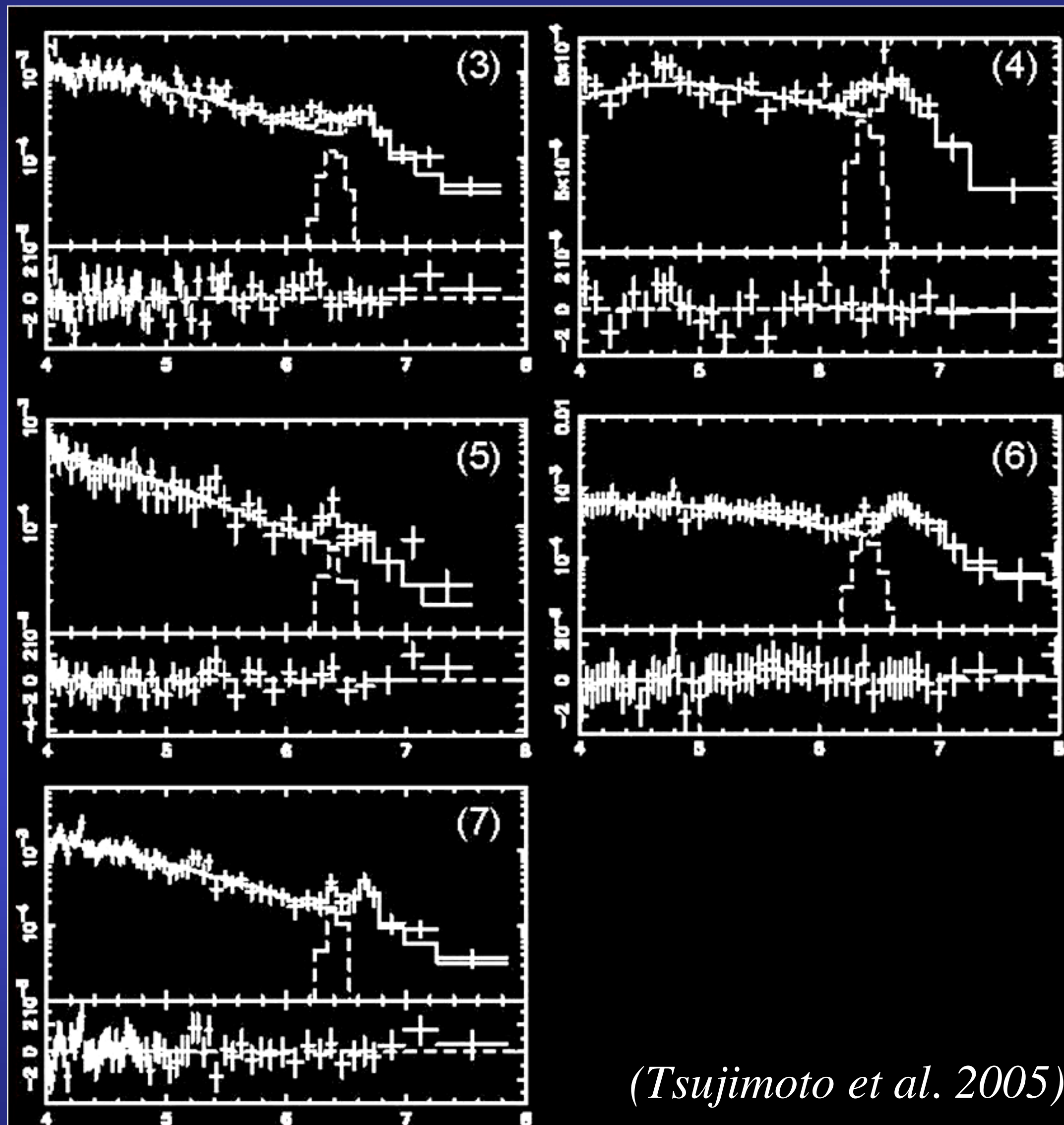
\- ionization : coupling with B: jets, etc. (Glassgold et al. 2000)
\- ***fluorescence ?*** YLW16A (Class I) (Imanishi et al. 2001)





Flare light curve and spectrum from Class I protostar YLW 16A, observed with Chandra ACIS (Imanishi et al. 2001)

The Magnificent Seven: fluorescing sources in Orion…



(Tsujimoto et al. 2005)

See also El29 (Cl. I) in ρ Oph

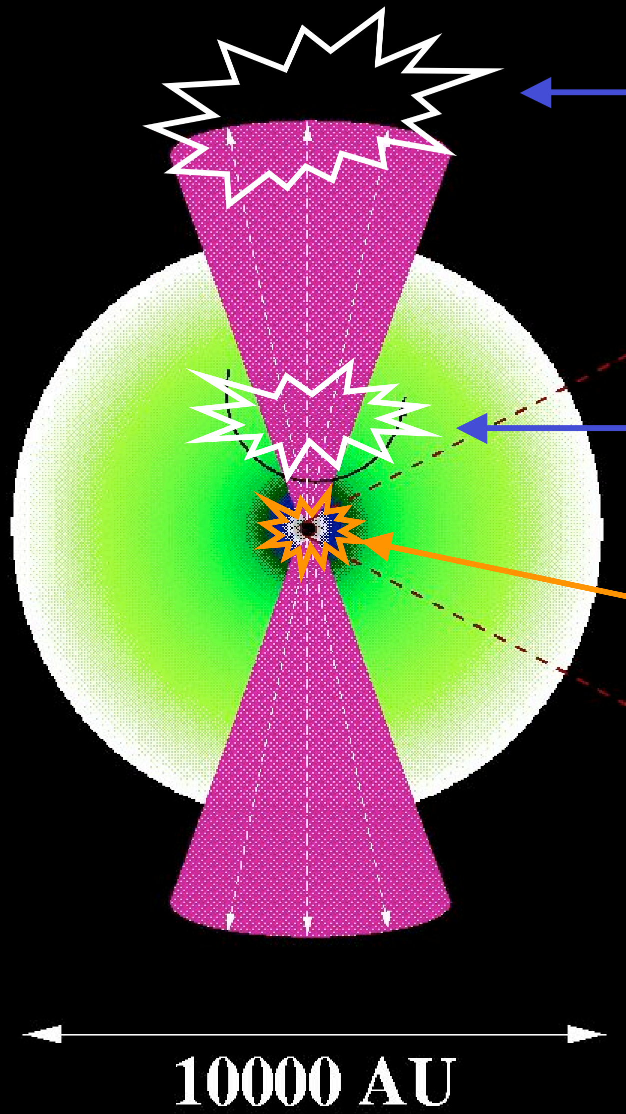
(Favata et al. 2004)

… out of 1616 ! Uncharacterized (Cl. I, II ?)

Chandra Orion Ultradeep Project

Jets

Jet-induced X-rays : shock heating



at the bow shock
(HH2, Pravdo et al.)

and/or

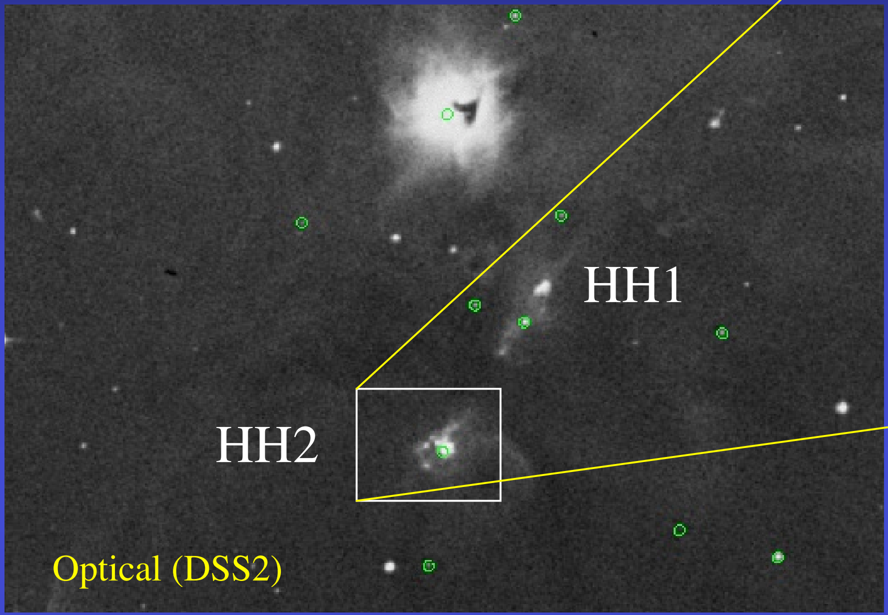
at the funnel wall
(L1551, Bally et al.)

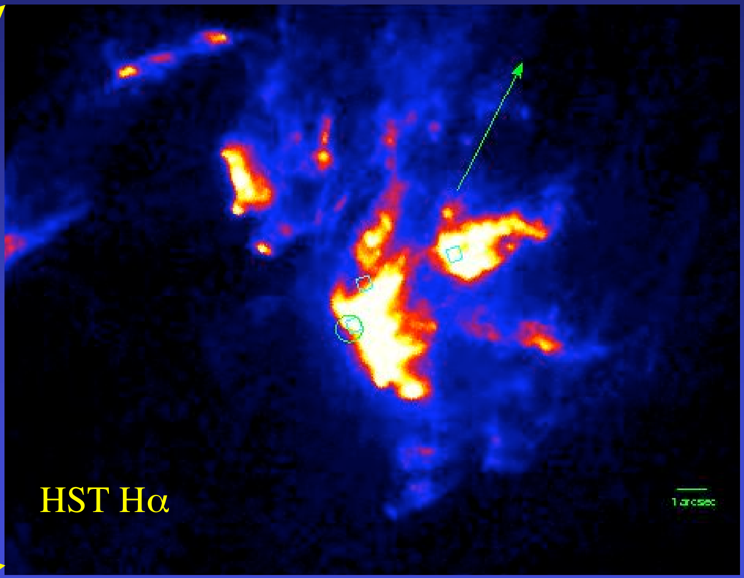
+ *from stellar magnetic activity*

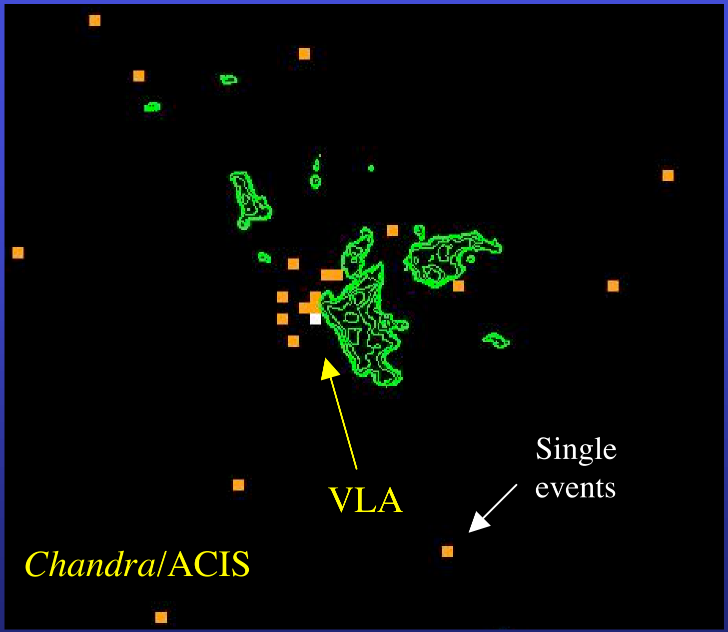
Conditions for detection :

- *high speed (> 300-400 km s^{-1})*
- *moderate extinction (A_V < 50)*

Herbig-Haro objects !







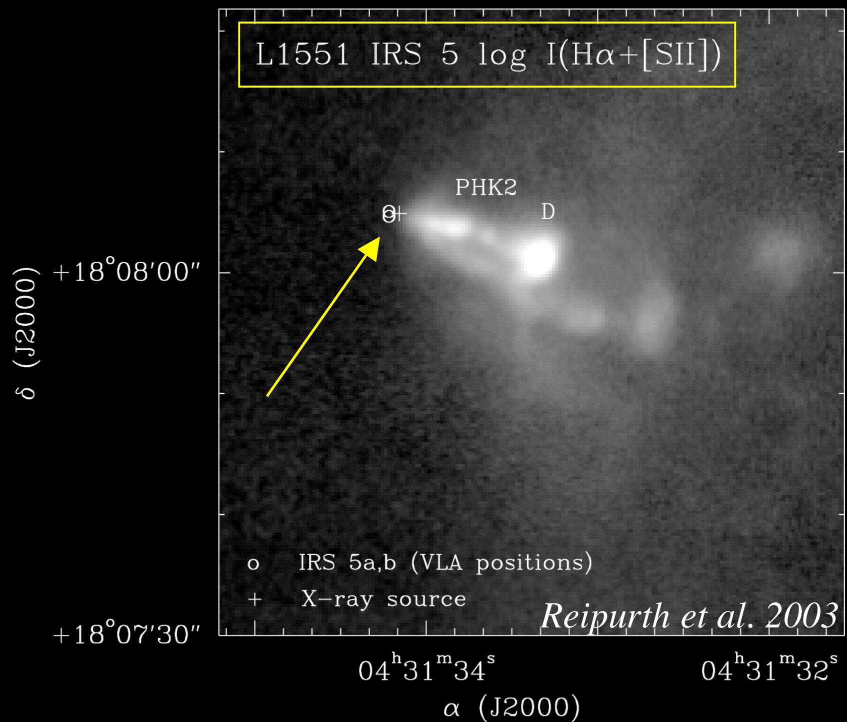
X-rays from HH2: **shocked material heated to ~ 10^6 K**

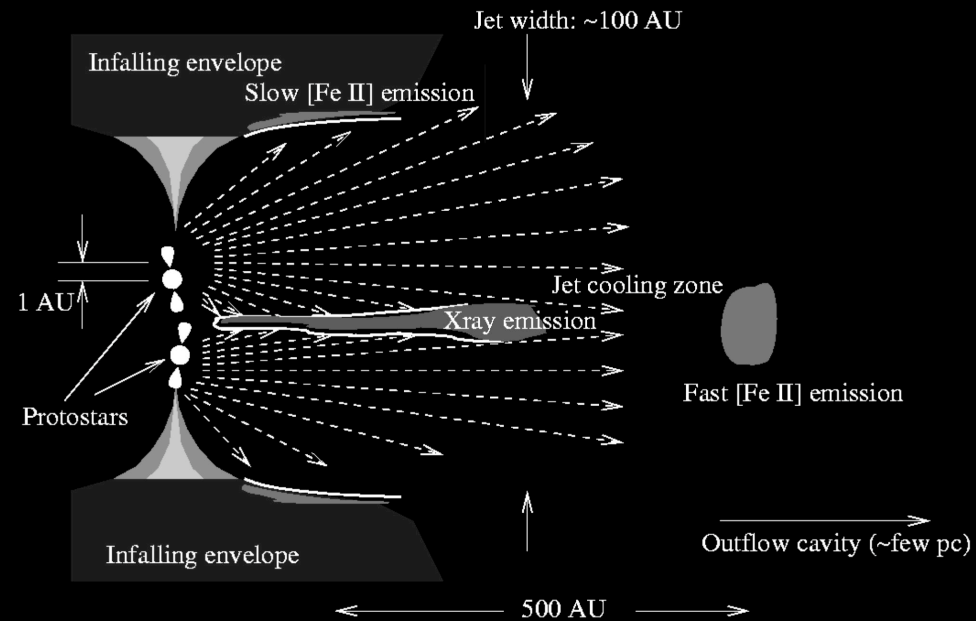
(Pravdo et al. 2001, *Chandra*)

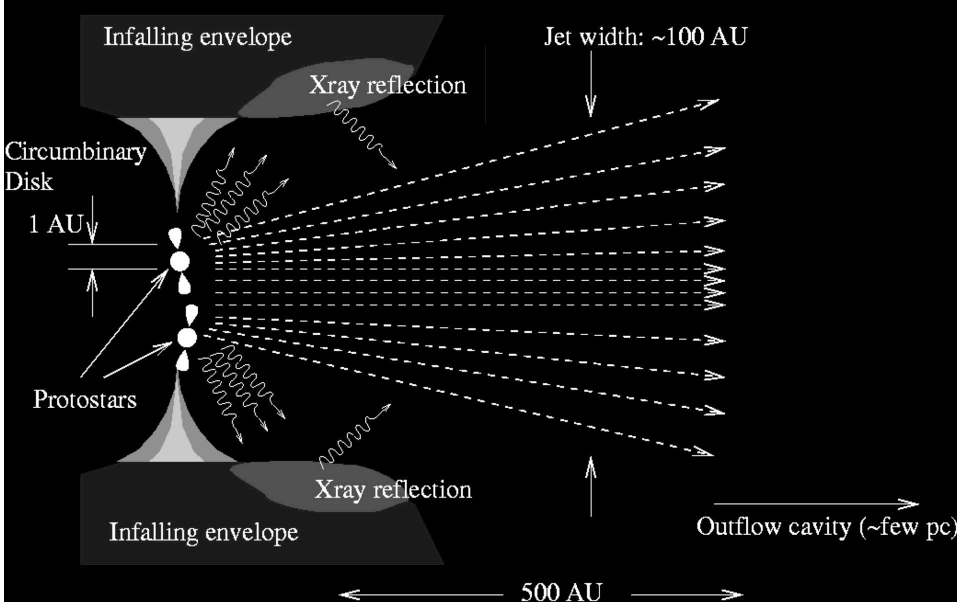
Other case: L1551

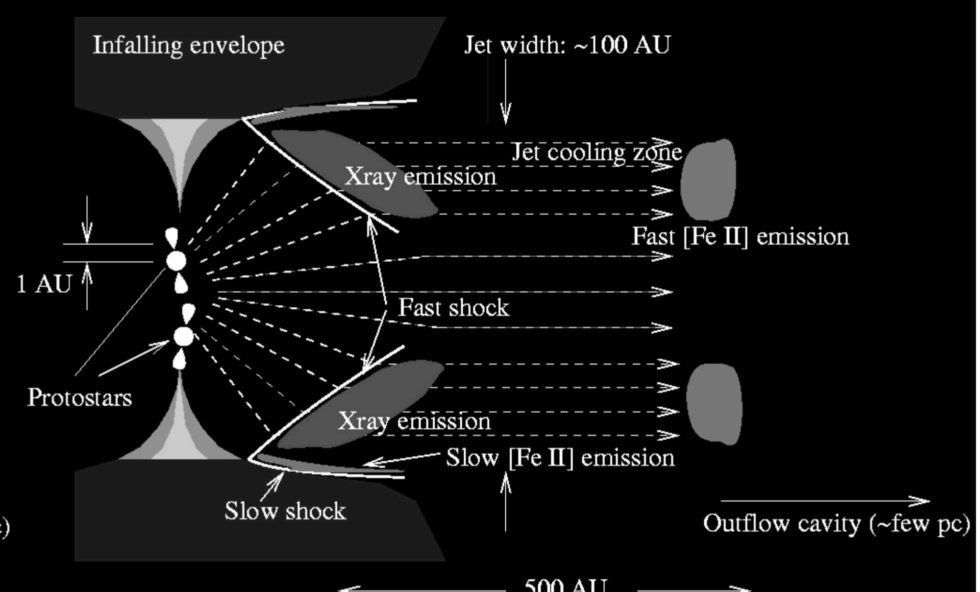
(Favata et al. 2001, XMM

Bally et al. 2002, *Chandra*)


L1551 IRS 5 log I(Hα+[SII])
PHK2
D
o IRS 5a,b (VLA positions)
+ X-ray source
Reipurth et al. 2003
δ (J2000)
+18°08′00″
+18°07′30″
04h31m34s
04h31m32s
α (J2000)

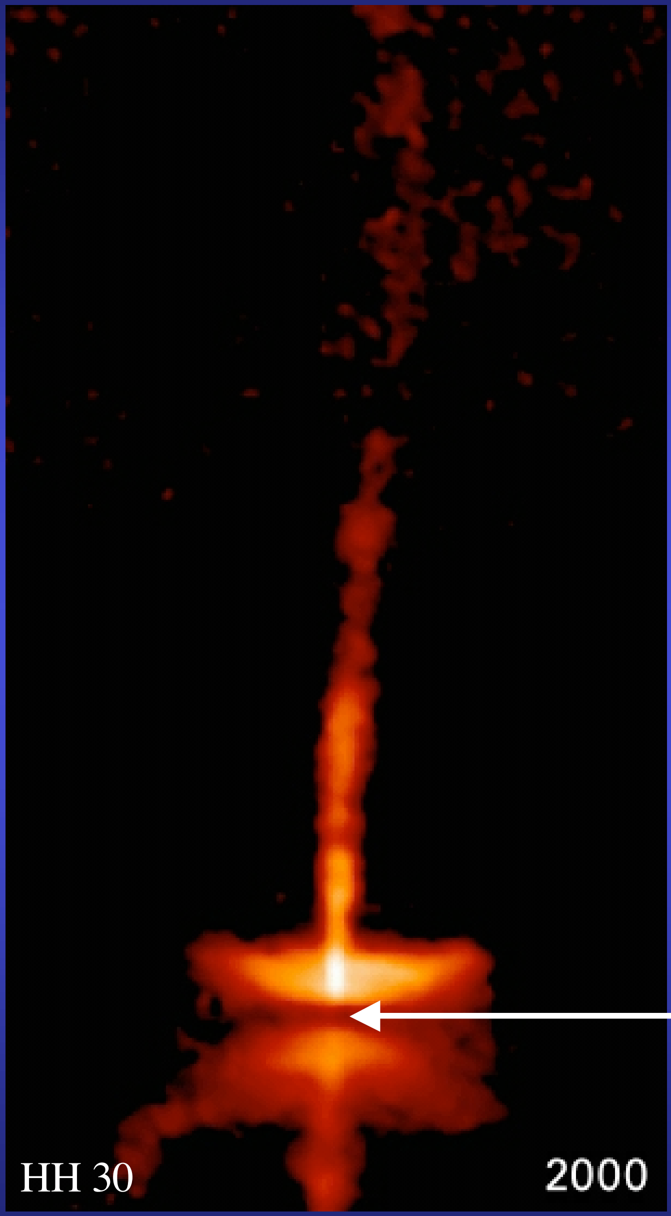

Jet width: ~100 AU
Infalling envelope
Slow [Fe II] emission
1 AU
Jet cooling zone
Xray emission
Fast [Fe II] emission
Protostars
Infalling envelope
Outflow cavity (~few pc)
500 AU


Infalling envelope
Xray reflection
Jet width: ~100 AU
Circumbinary
Disk
1 AU
Protostars
Xray reflection
Infalling envelope
Outflow cavity (~few pc)
500 AU


Infalling envelope
Jet width: ~100 AU
Jet cooling zone
Xray emission
Fast [Fe II] emission
1 AU
Fast shock
Protostars
Xray emission
Slow [Fe II] emission
Slow shock
Outflow cavity (~few pc)
500 AU

4. Results from X-ray observations (2)

From Class I to Class 0

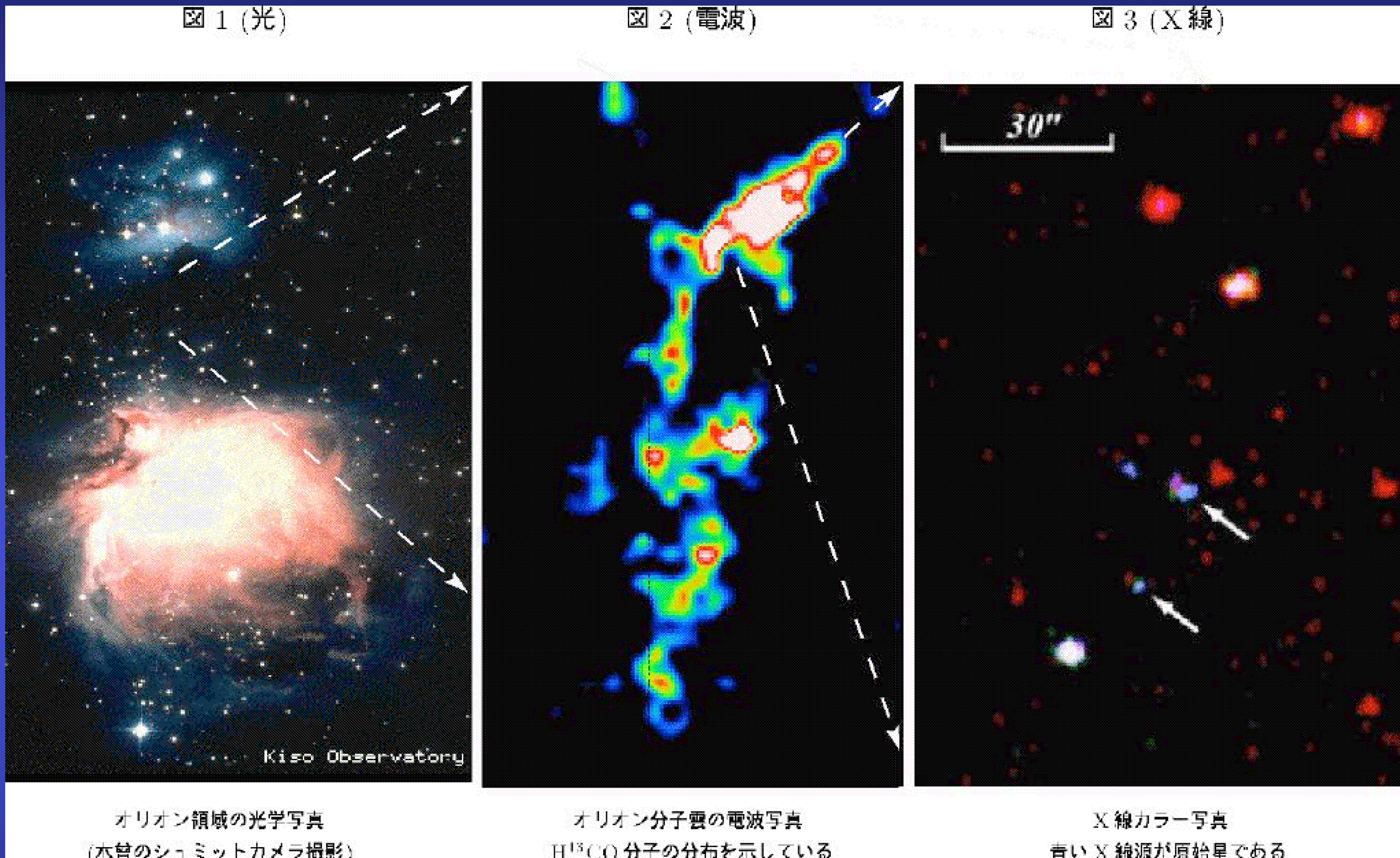


Class I/II sources can be extremely optically thick, mimicking Class 0 sources.

However some IR gets out by scattering => if IR is detected, the envelope is thin and it's not a Class 0

X-ray emission may be detected from the jet bowshock(s), if N_H is not too high there

$A_V > \times 1000$!



Two "candidate Class 0 sources" detected by *Chandra* (Tsuboi et al. 2001) in Orion OMC 2/3 turned out to be high-speed jets (Tsujimoto et al. 2004)

Class 0 sources are hard to detect !

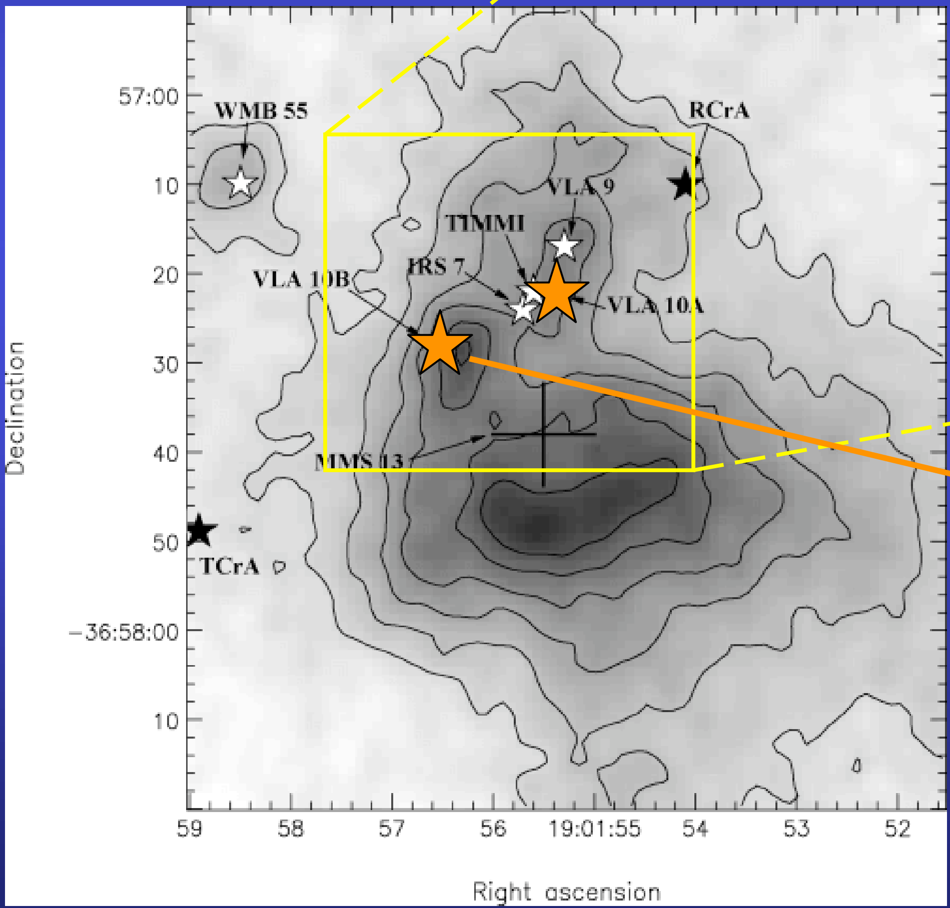
(sample of 11; more expected)

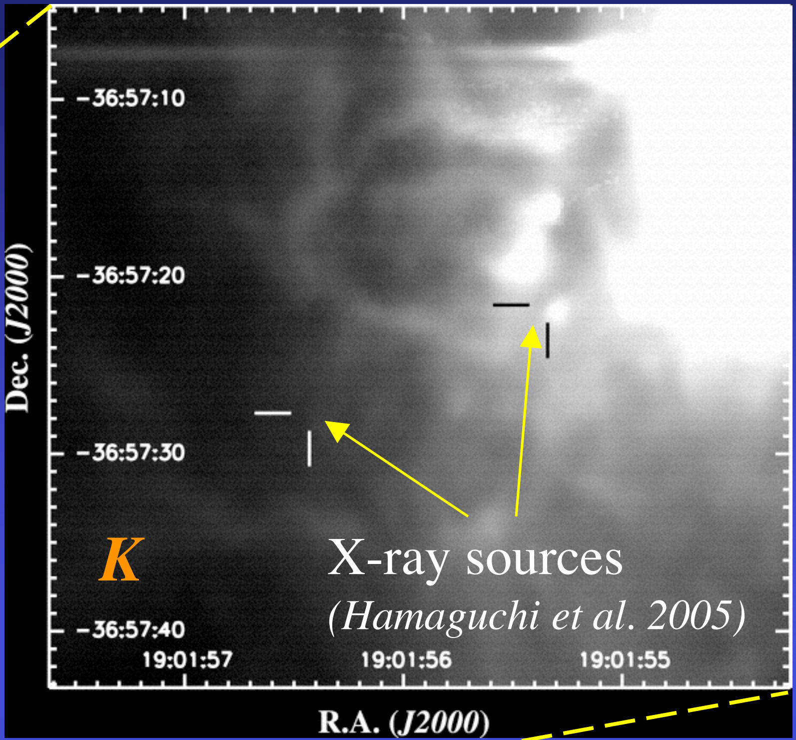
Region	Name Cl. 0	Sat.	Exp. (ksec)	D (pc)	Lbol (Lsol)	Lx < (erg/s) Av=100, T=2 keV	Lx/Lbol < Av=100, T=2 keV	Lx < (erg/s) Av=100, T=5 keV	Lx/Lbol < Av=100, T=5 keV	Lx < (erg/s) Av=500, T=2 keV	Lx/Lbol < Av=500, T=2 keV	Lx < (erg/s) Av=500, T=5 keV	Lx/Lbol < Av=500, T=5 keV
L1448	L1448-C	XM	30	300	9	4.0E30	2.2E-4	1.5E30	8.4E-5	7.6E31	4.2E-3	1.7E31	9.6E-4
NGC1333	IRAS2,4A,4B	Ch	50	350	40	1.0E30	1.3E-5	3.8E29	4.7E-6	2.0E31	2.5E-4	4.8E30	6.0E-5
	SVS13B				7	1.0E30	7.1E-5	3.8E29	2.7E-5	2.0E31	1.4E-3	4.8E30	3.4E-4
IC348	HH211-MM	Ch	50	300	5	7.7E29	7.7E-5	2.8E29	2.8E-5	1.5E31	1.5E-3	3.6E30	3.6E-4
Taurus	IRAM04191	Ch	20	140	0.15	4.2E29	1.4E-3	1.5E29	5.0E-4	8.1E30	2.7E-2	1.9E30	6.4E-3
Taurus	L1527	Ch	20	140	2	4.2E29	1.0E-5	1.5E29	3.8E-5	8.1E30	2.0E-3	1.9E30	4.8E-4
L1641-N	VLA1	XM	50	450	50	5.4E30	5.4E-5	2.1E30	2.1E-5	1.0E32	1.0E-3	2.3E31	2.3E-4
Rho Oph A	VLA1623	Ch	100	150	1	9.6E28	4.8E-5	3.5E28	1.7E-5	1.9E30	9.3E-4	4.4E29	2.2E-4
L1688	IRAS16293	Ch	30	150	23	3.2E29	7.0E-6	1.2E29	2.5E-6	6.2E30	1.4E-4	1.5E30	3.2E-5

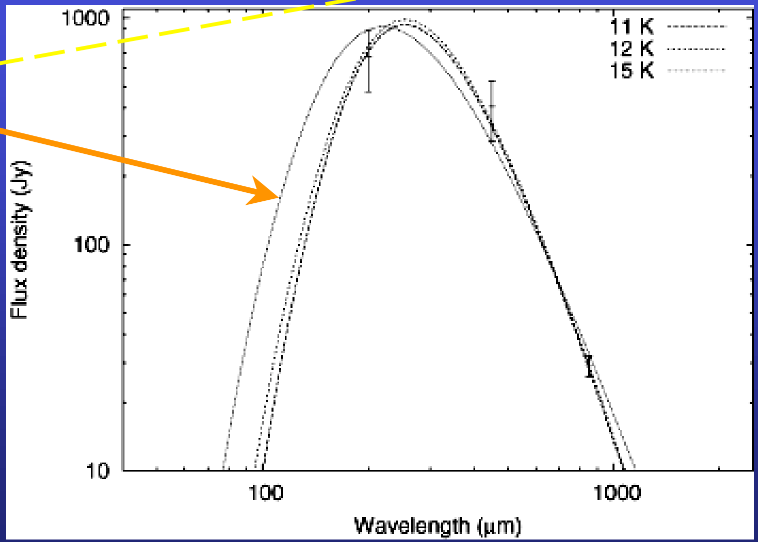
Montmerle et al. in prep. (incl. literature)

Upper limits $L_X/L_{bol} \sim 10^{-5}$ are significant, compared with Class I and TTS detections...

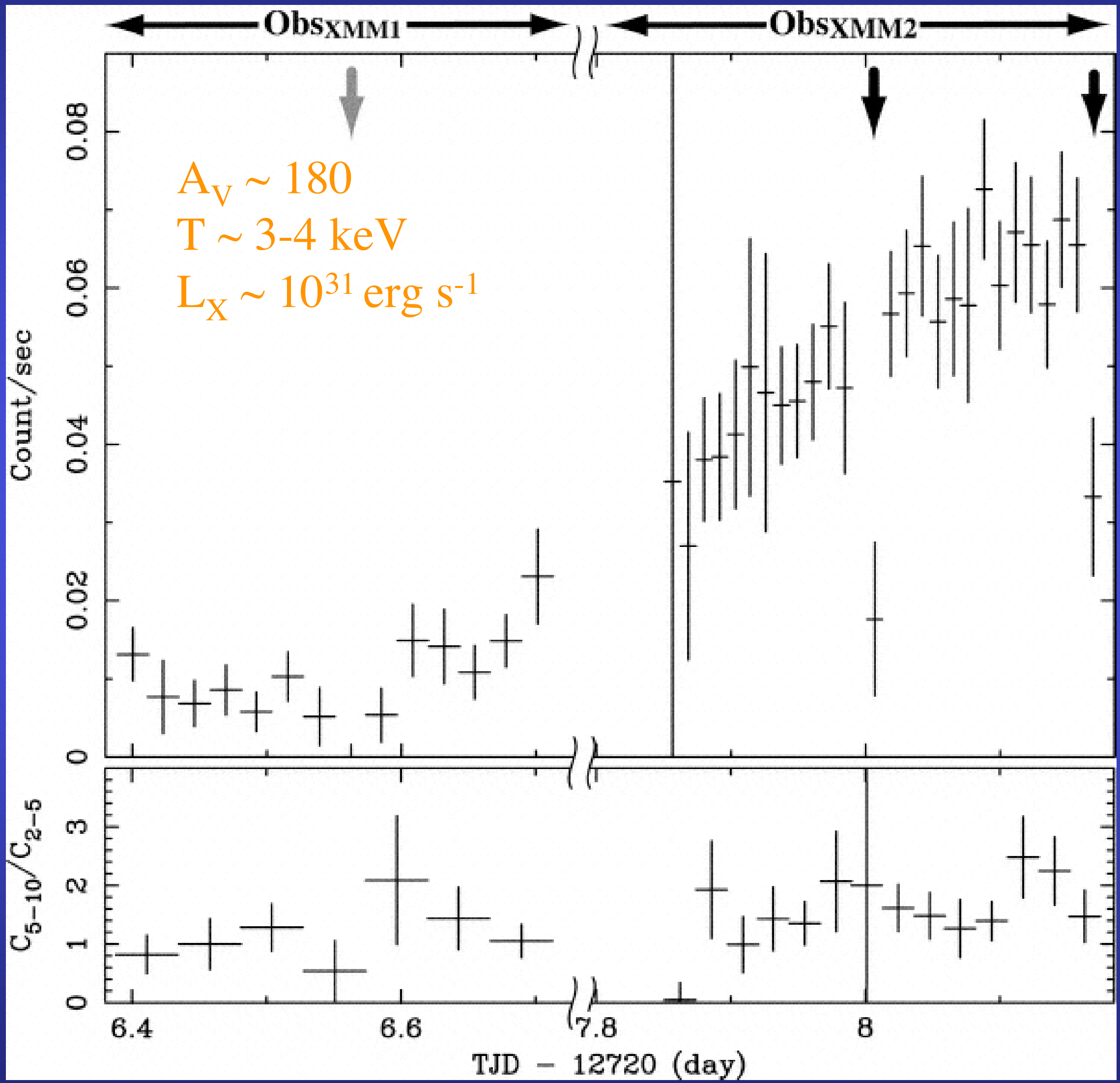
The R CrA region at mm wavelengths (André et al. 2005)





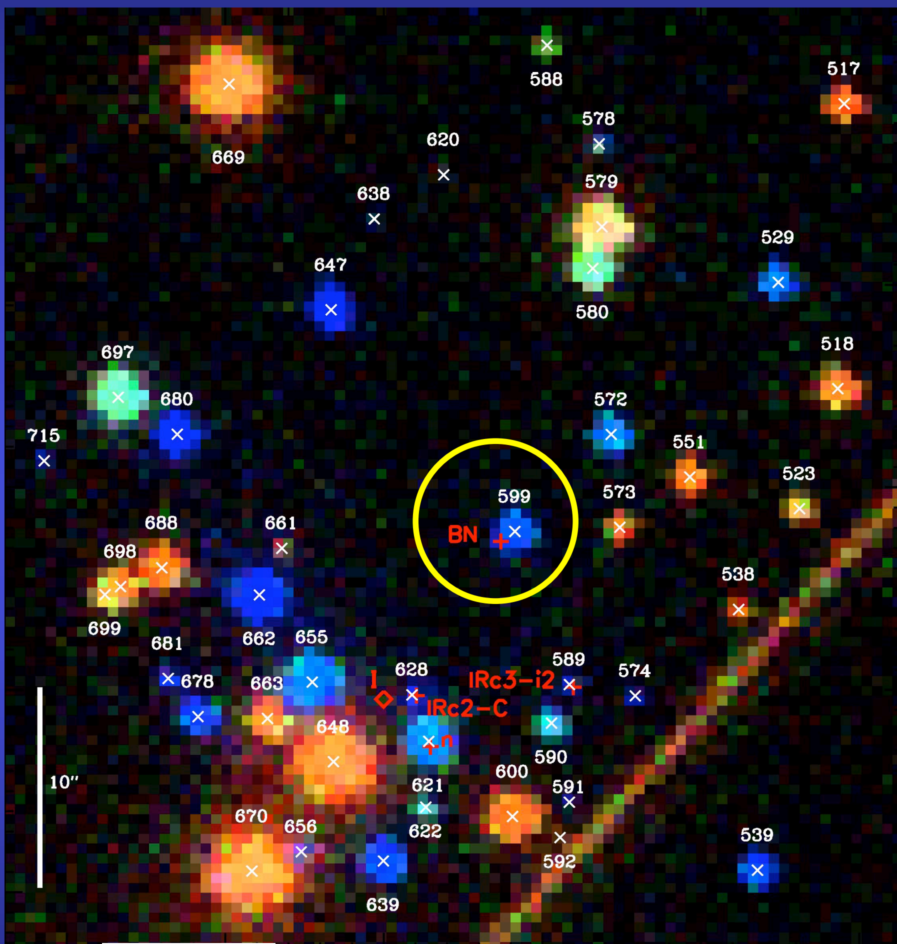


The “X_E” source in R CrA



Massive protostars ?

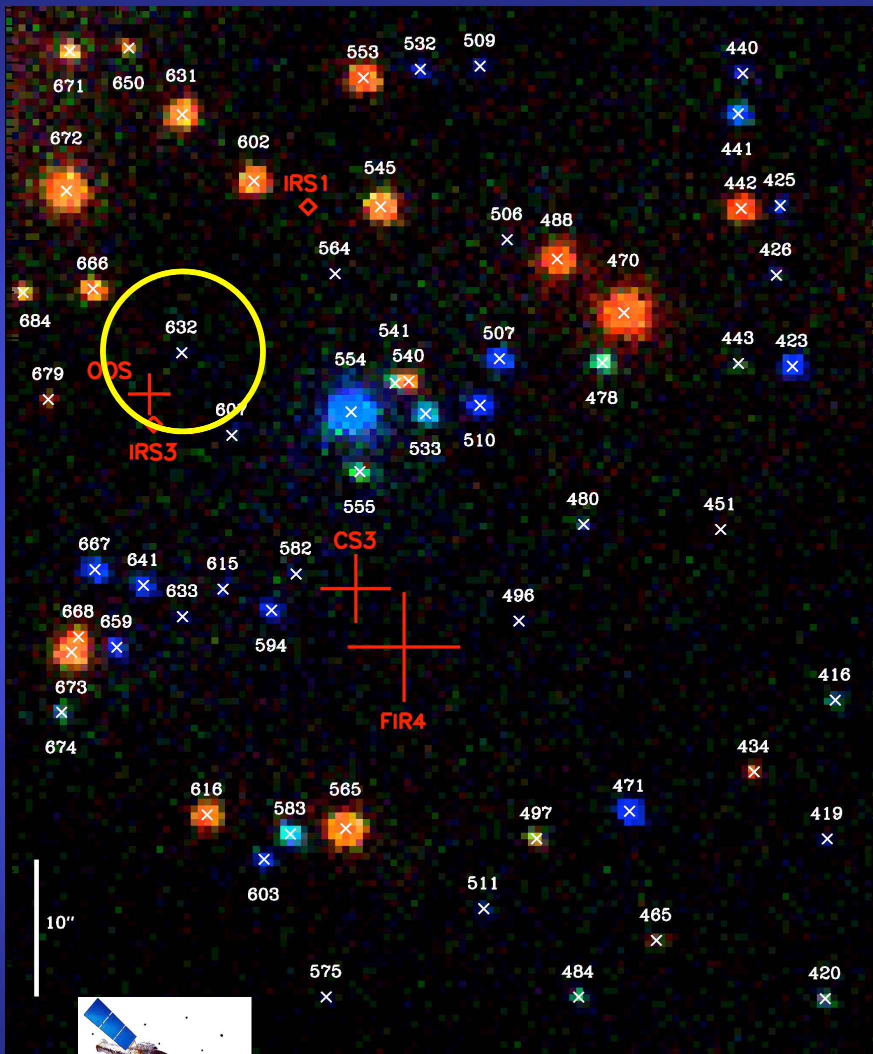
The BN/KL massive protostar cluster region in the ONC



The BN object is detected (?), but very faint

$A_V \sim 50$, $L_X \sim 10^{29}$ erg s^{-1} (Grosso et al. 2005)

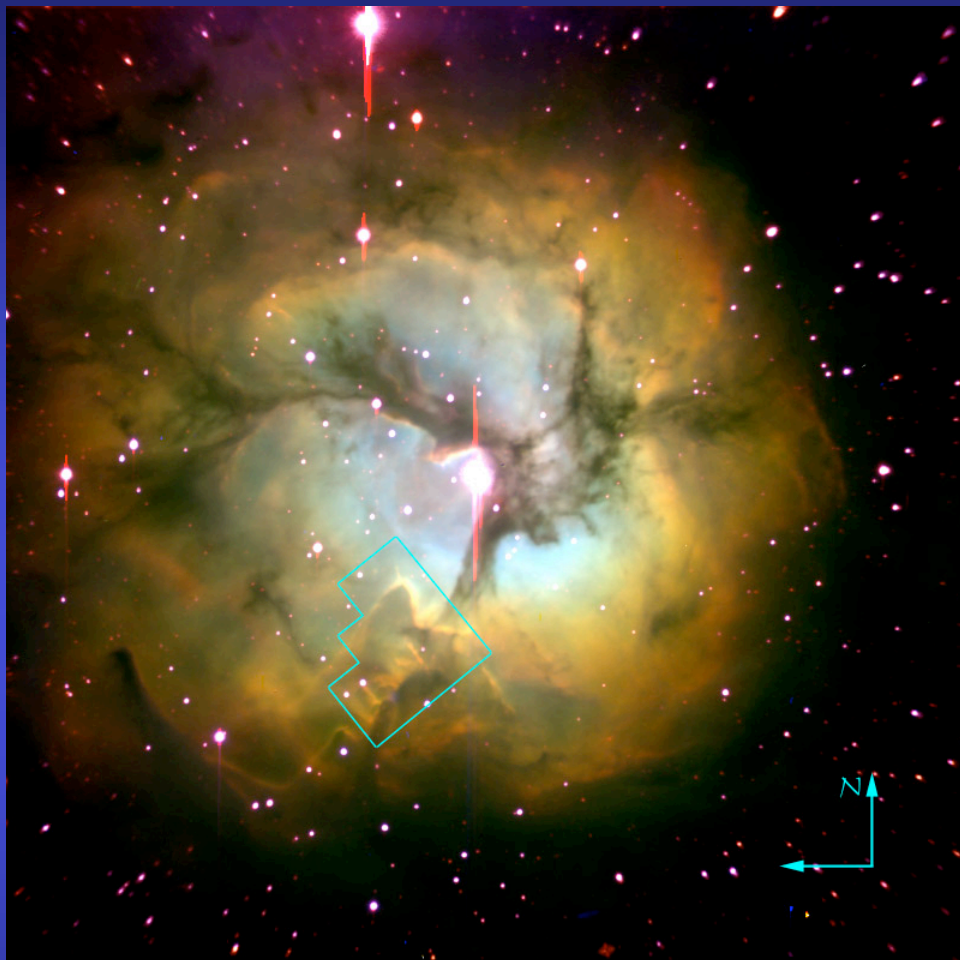
Deeply embedded X-ray sources in OMC-1 South

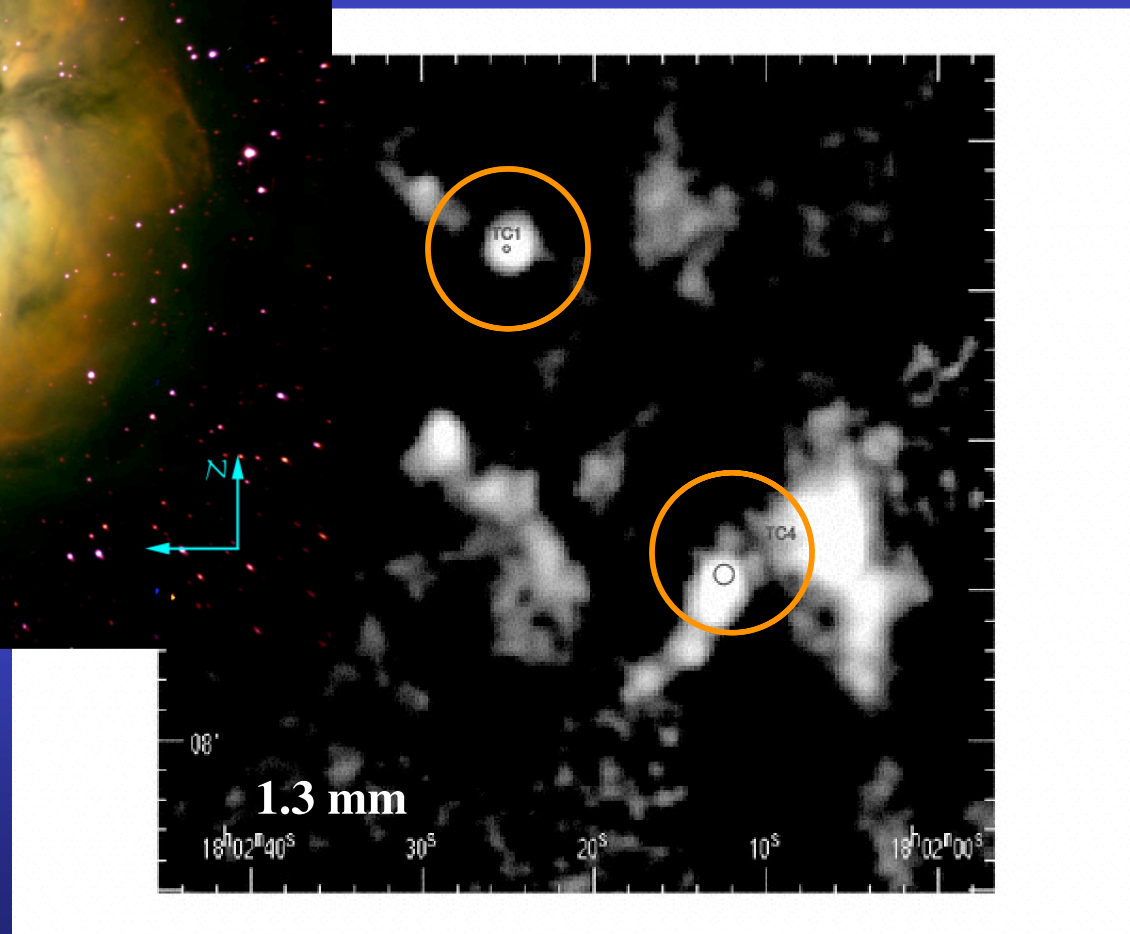


COUP 632 has A_V ~ 500 ! => protostar ? (Grosso et al. 2005)

The Trifid nebula (M20)

d ~ 1.7 - 2.8 kpc; O7.5





(Rho et al. 2004)

5. Conclusions & open issues (1)

- *Class I protostars: maturing field*
  - many source detections (det. rate > 80 %)
  - a few jets detected (det. rate < 10 %): requires high shock speeds + low extinction
  - + a few examples of fluorescence line (det. rate ~ few %): requires high flux + favorable disk irradiation geometry/viewing angle
  - X-ray properties globally similar to TTS; but *higher T*
- *Class 0 protostars: many instrinsic obstacles*
  - *Very low detection rate:* 1 detected, combined XMM + Chandra
  - **Very high extinctions**, even for hard X-rays
  - May be eased if viewing geometry favorable (i.e., ~ along funnel); no access to possible soft component

5. Conclusions & open issues (2)

- *Class I protostars*
  - As for Class II TTS, what is the relation between the observed X-rays (magnetic activity) and the large-scale magnetic field channeling the accretion and the ejection ?
  - Do the star and the disk necessarily corotate ? f(M_*) ?
- *Class 0 protostars*
  - First detection very important, but puzzling: L_X comparable to Class I, but very different light curve => special case ?

    But: the central star does not exist yet !
  - => Is X-ray emission the « birth cry » of stars, i.e., when they start to exist as gravitationally bound bodies, with convection fueling some form of (yet unseen, or non-solar…) magnetic activity ?
- *The accretion-ejection phenomenon in time*
  - History ? Variable accretion (FUOr or EXOr events) ?
  - Magnetic field evolution ? (Dynamo, topology, intensity…)