A photograph of a snowy mountain landscape at dusk or dawn. The sky is a deep, dark blue-grey, and a small, bright white circle is visible in the upper left quadrant. The mountains are covered in snow, with some dark patches of rock or vegetation visible. In the foreground, there are dark evergreen trees and a snow-covered slope. The overall scene is serene and atmospheric.

*Chronologie de la formation du
système solaire (III: Aussois 2006):
résumé des épisodes précédents,
nouveaux éclairages sur les mêmes problèmes...*

Thierry Montmerle

Laboratoire d'Astrophysique de Grenoble, France

Introduction:

quelques (vastes) questions...

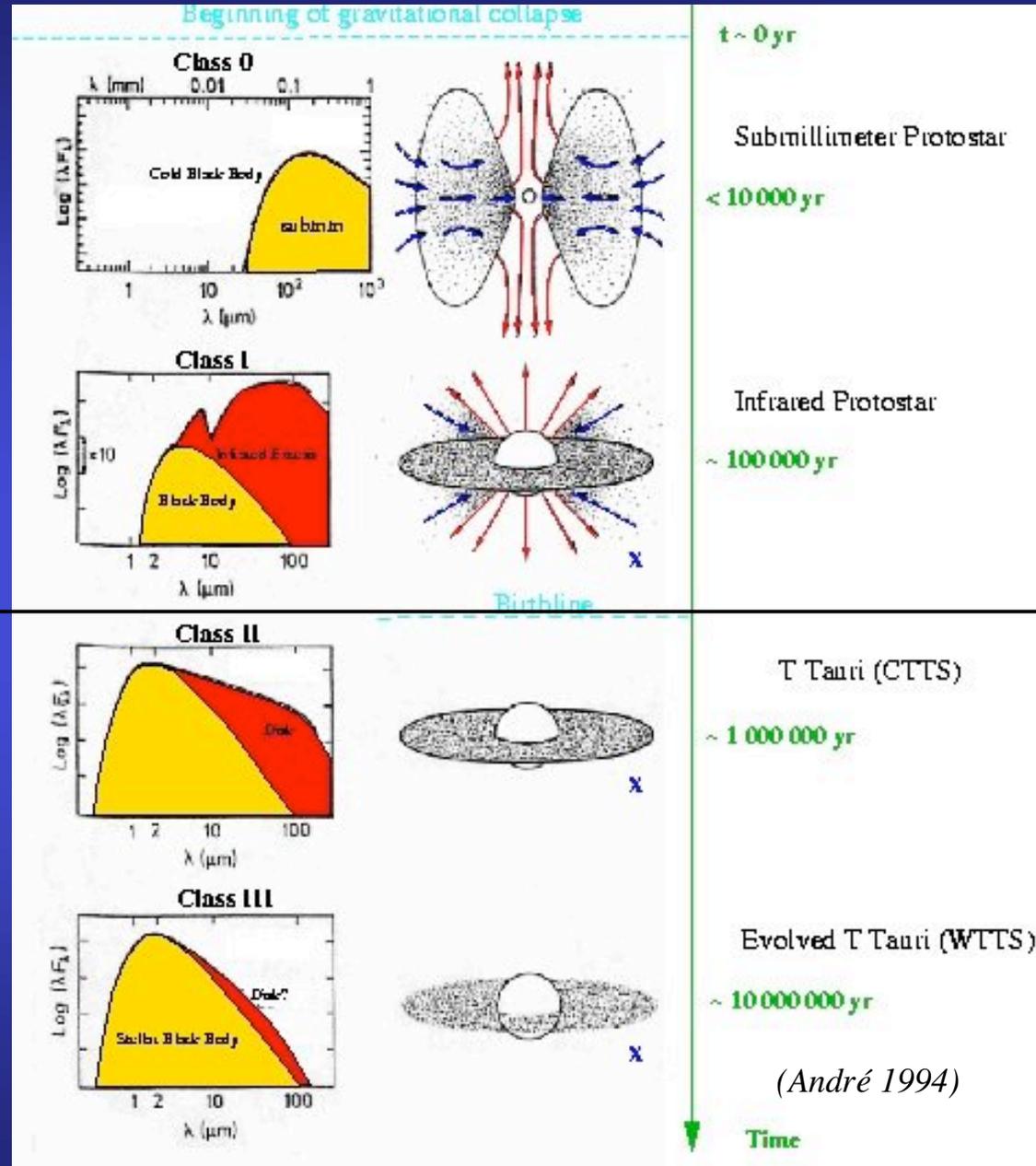
- Où, quand et comment le Soleil s'est-il formé ?
- Comment le système solaire s'est-il formé ?
- *Méthode:*
 - Observation des étoiles jeunes de type solaire dans les régions de formation d'étoiles (+ théorie et modélisation)
 - Données "fossiles" sur le système solaire jeune (météorites)
 - "*Chrono*" I (2002) & II (2004): les premières étapes

1. Formation et évolution des étoiles de type solaire

Main stages of evolution of low-mass stars

Protostars
(embedded stage)

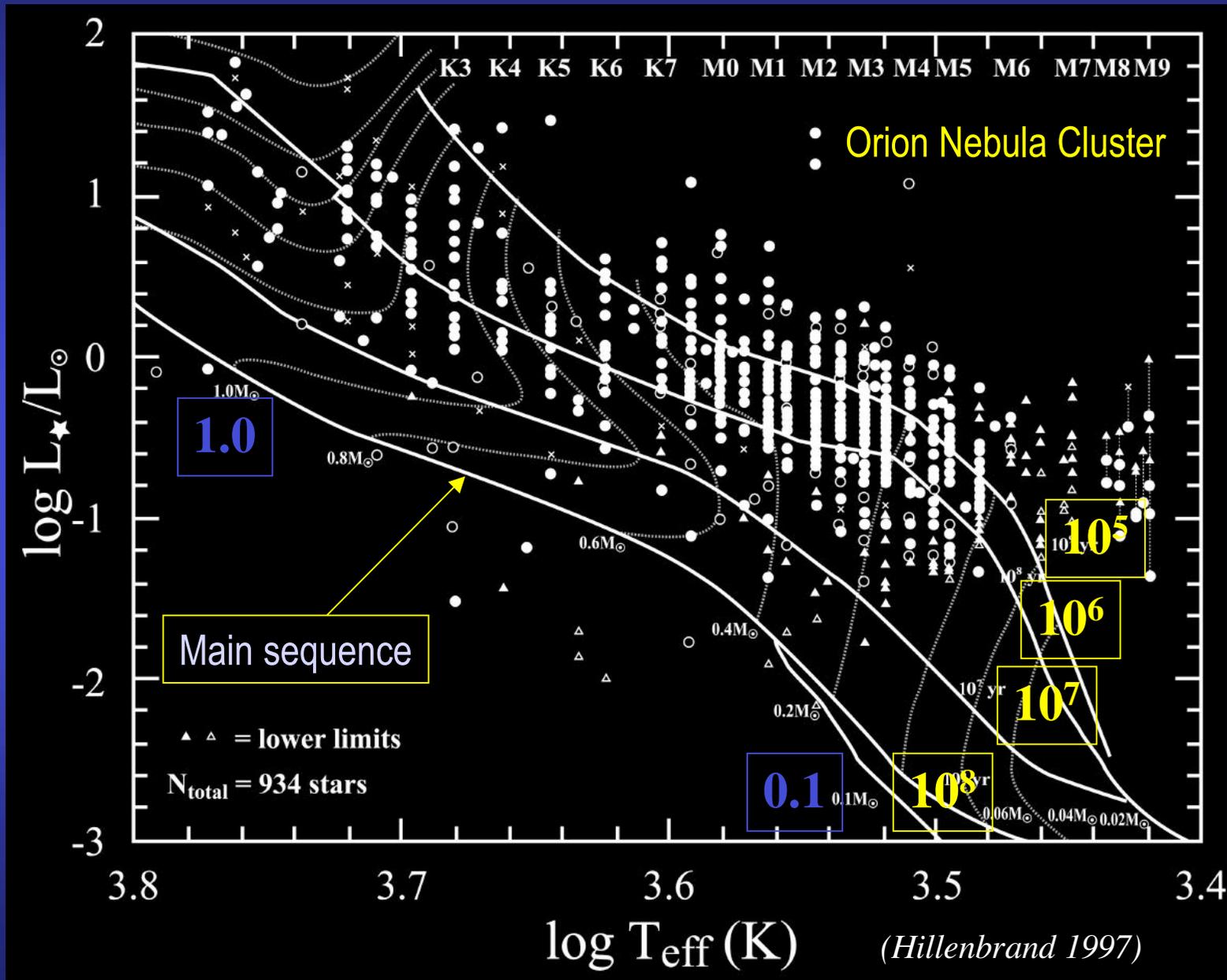
T Tauri stars
(visible stage)

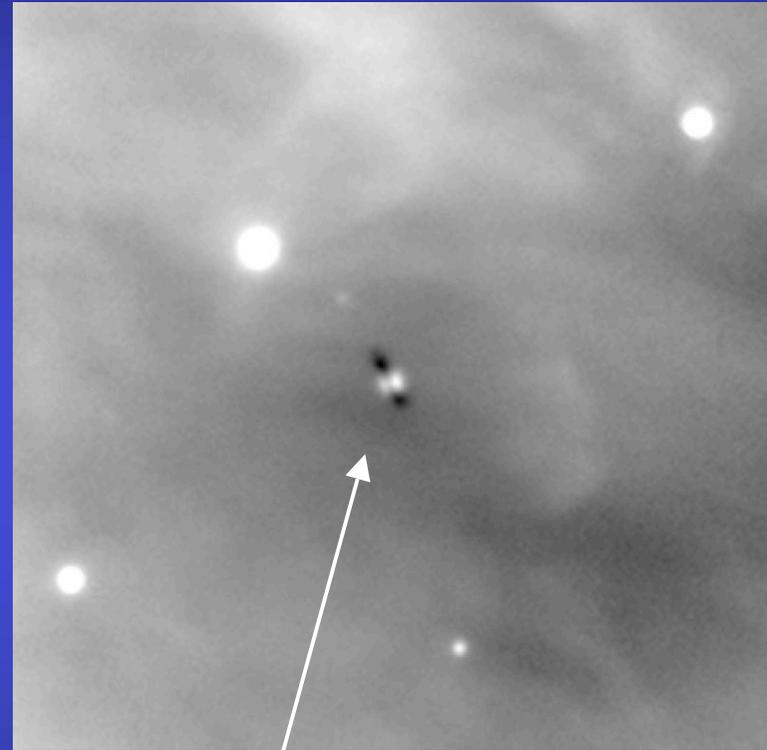
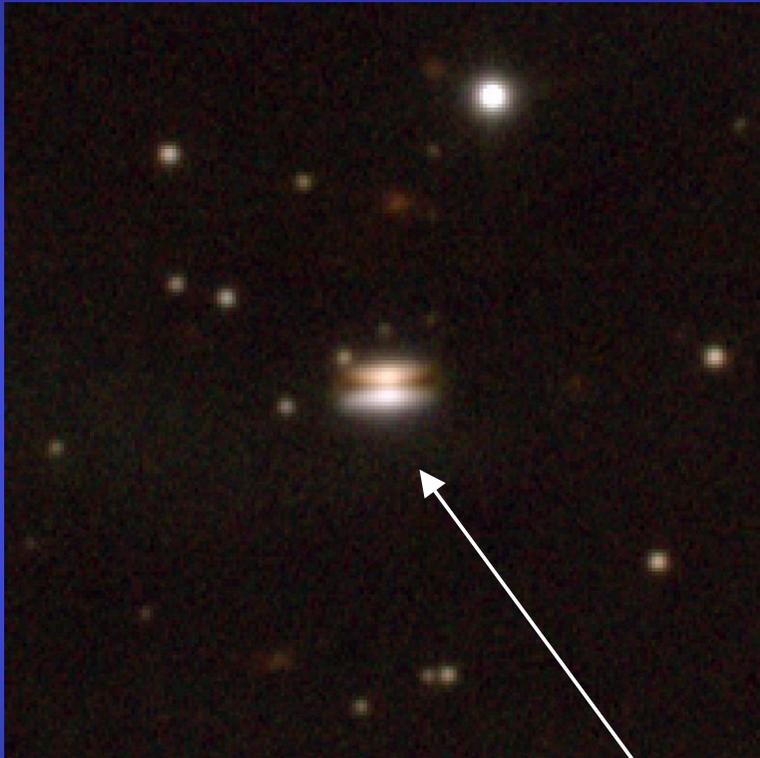


PROPERTIES	<i>Infalling Protostar</i>	<i>Evolved Protostar</i>	<i>Classical T Tauri Star</i>	<i>Weak-lined T Tauri Star</i>	<i>Main Sequence Star</i>
SKETCH					
AGE (YEARS)	10^4	10^5	$10^6 - 10^7$	$10^6 - 10^7$	$> 10^7$
mm/INFRARED CLASS	Class 0	Class I	Class II	Class III	(Class III)
DISK	Yes	Thick	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

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.)

Le diagramme de Hertzsprung-Russell (obs): masses et âges (théorie)





Le Soleil est-il né ici (ρ Oph) ou là (Orion) ? Ou autre ?

*Différents types de
régions de formation d'étoiles...*

$M_{*,\text{max}} \sim 2 \text{ à } 100 M_{\odot}$

$N_* \sim 10^2 \text{ à } > 10^4$ (cf. IMF)



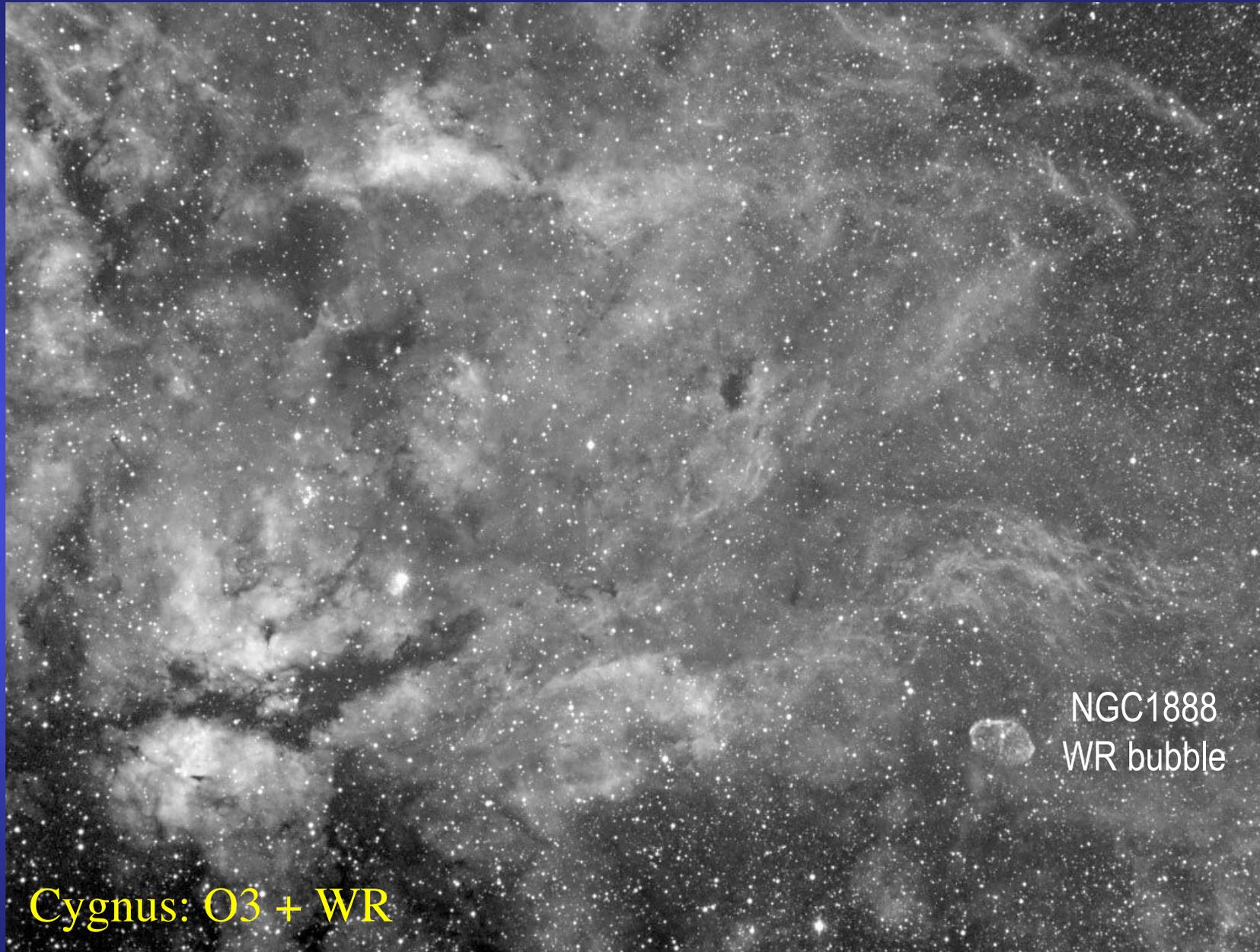
Orion: O7



ρ Oph: B2



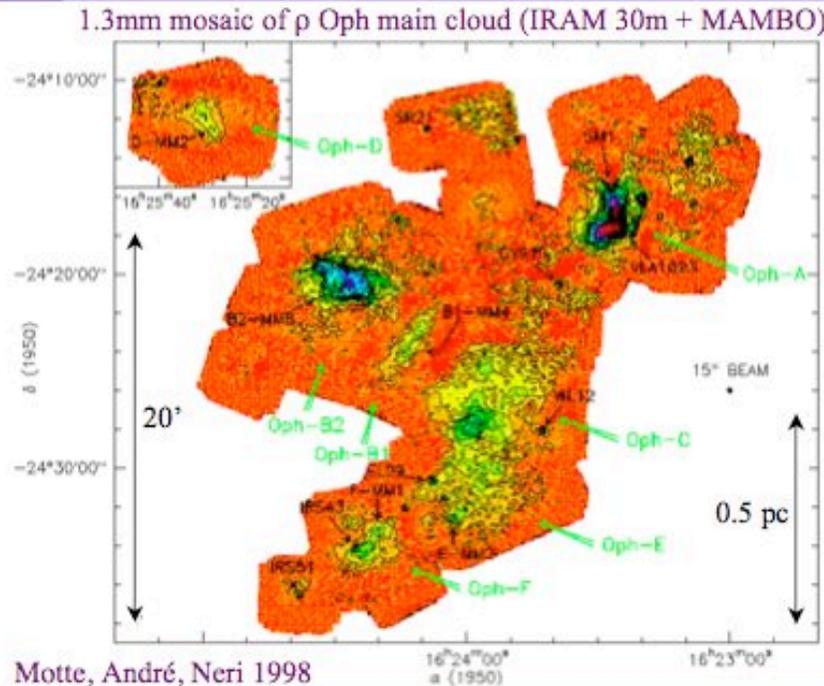
Rosette: O4



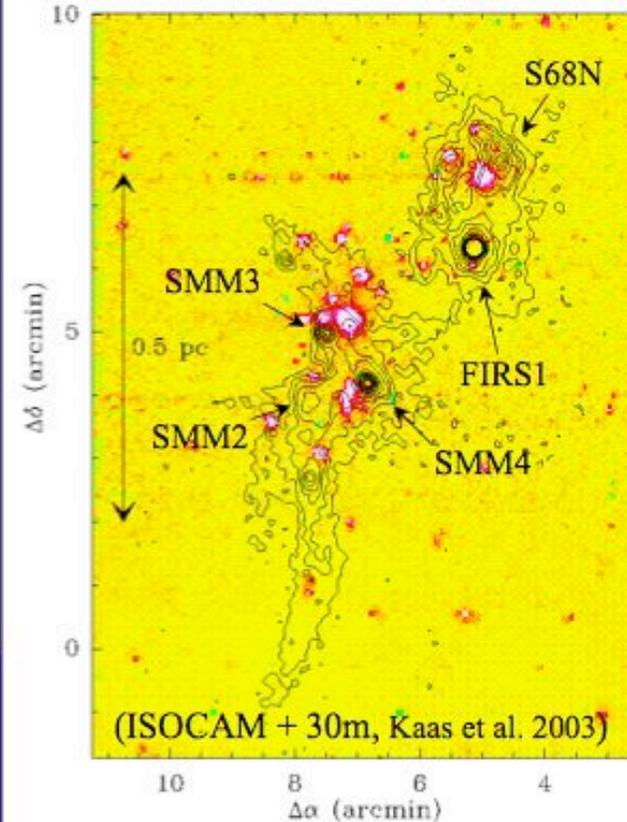
Cygnus: O3 + WR

NGC1888
WR bubble

Recensements de proto-étoiles de «Classe 0» et condensations «pré-stellaires» en continuum (sub)-millimétrique



The Serpens Core ($d = 310$ pc) at $7 \mu\text{m}$ and 1.3 mm



Statistique :

Préstellaire / Classe 0 / Classe I / Classe II

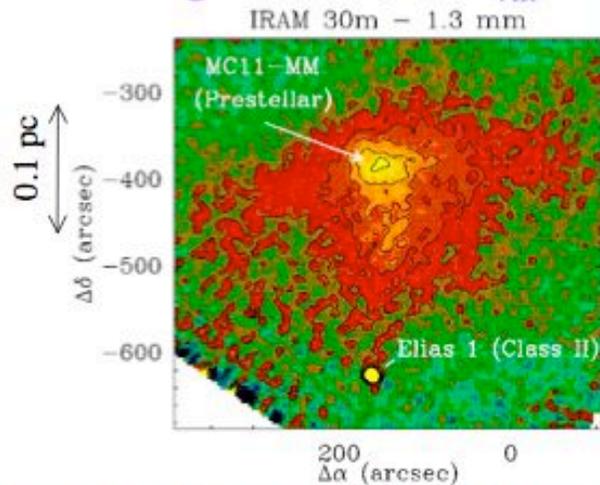
ρ Oph : 0.52 / 0.02 / 0.13 / 1

Serpent : 0.46 / 0.09 / 0.36 / 1

Durée de vie de la Classe II $\sim 10^6$ ans

(Ph. André, Aussois 2004)

Cœurs pré-stellaires :
Auto-gravitants ($M \sim M_{\text{VIR}}, M_* = 0$)

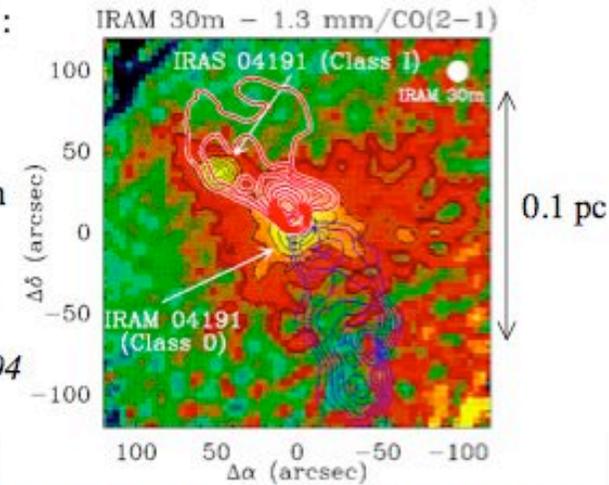


Traceurs d'évolution :

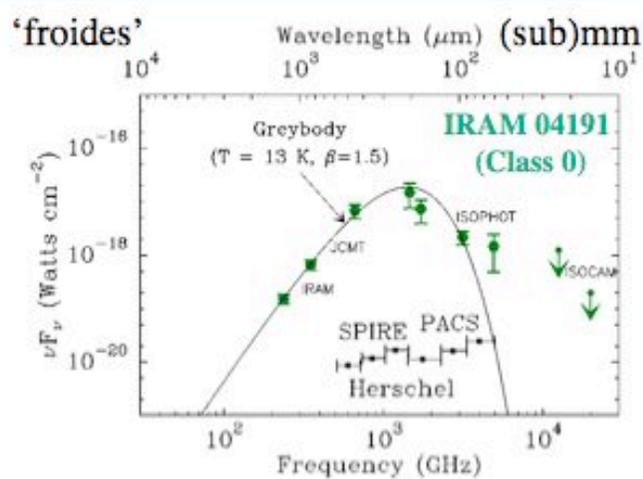
- Spectre d'énergie
Lada & Wilking '84;
Lada 1987
- Masse et distribution
de la matière en
continuum (sub)mm
André et al. '93;
André & Montmerle '94

$$M = \frac{S_{1.3} d^2}{B_{1.3}(T) \kappa_{1.3}}$$

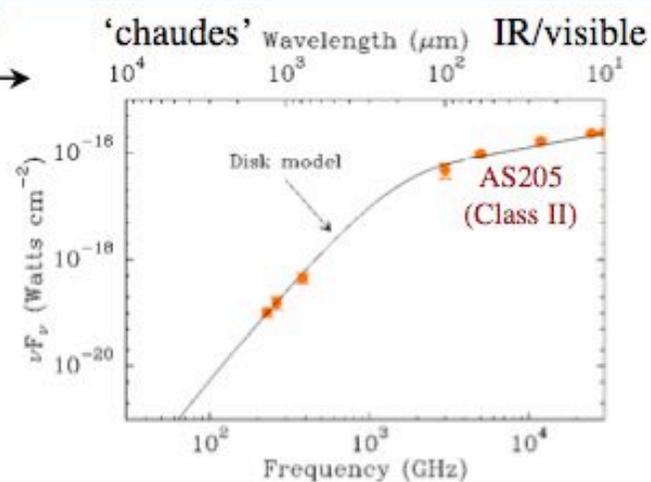
Protoétoiles de Classe 0 :
Enveloppe massive ($M_{\text{env}} > M_*$)



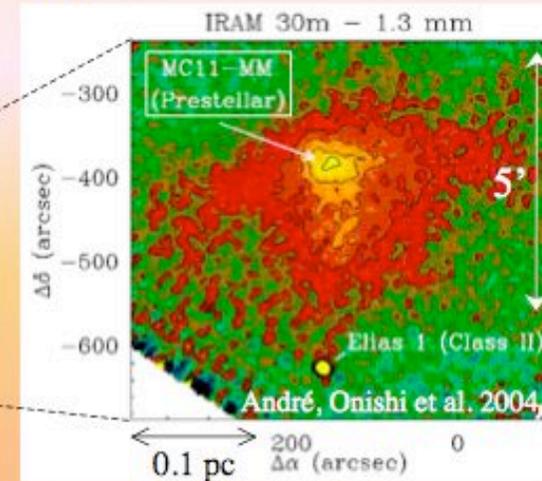
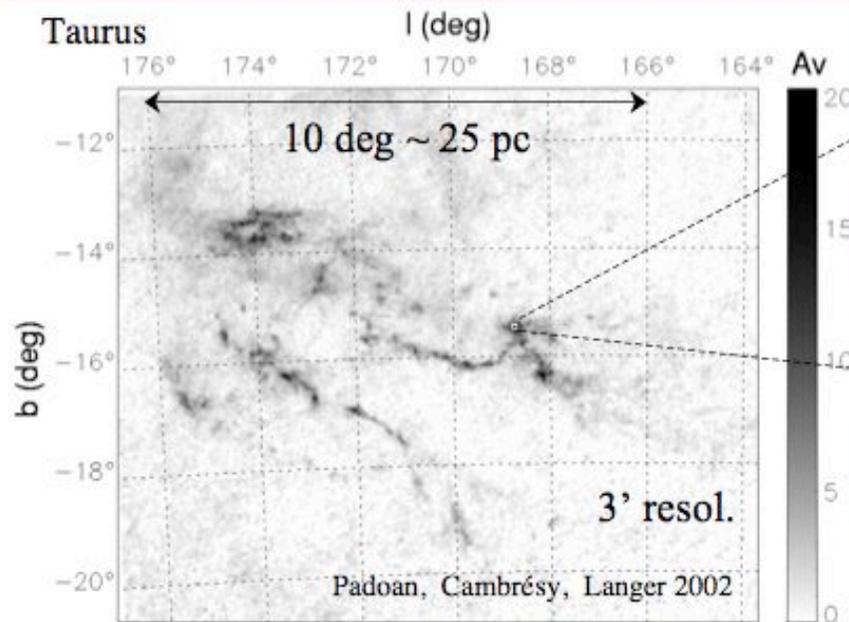
Classe I : Combinaison enveloppe + disque → Classe II : $M_{\text{env}} \sim 0$, disque dominant



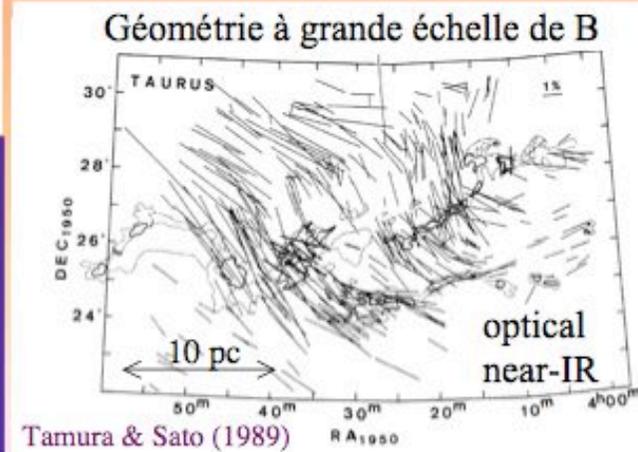
SEDs



Distribution des cœurs pré-stellaires le long de filaments: L'exemple du nuage du Taureau

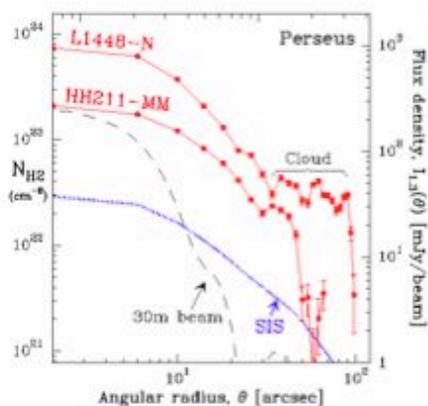


- Le mécanisme de formation des cœurs pré-stellaires est intimement lié au processus de formation des filaments dans les nuages
- Importance d'une compréhension globale des nuages incluant une grande gamme d'échelles spatiales



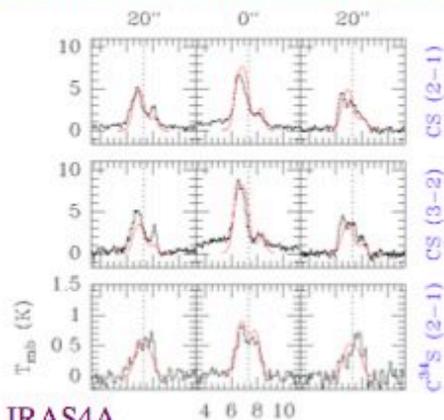
Effondrement plus violent dans les proto-amas (e.g. ρ Oph, Persée)

Enveloppes plus denses : au stade Classe 0, ~ 3 -12 fois plus denses qu'une SIS à $T = 10$ K



(Motte & André 2001)

Vitesses d'effondrement supersoniques



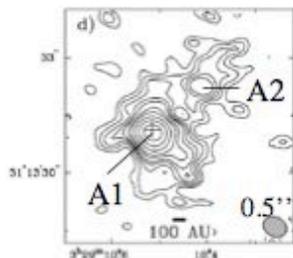
IRAS4A

$V_{\text{inf}} \sim 0.7$ -1.3 km/s, $\dot{M}_{\text{inf}} \sim 1$ -5 $\times 10^{-4}$ M_{\odot} /yr
à 2000 AU (Di Francesco et al. 2001;
Belloche et al., in prep.)

→ **Taux d'accrétion très élevés ($\gg a^3/G$) qui peuvent s'expliquer dans le cas d'une augmentation forte et rapide de la pression extérieure**

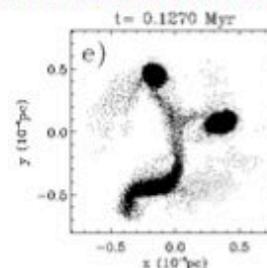
↓
Favorise la formation des systèmes multiples

IRAS4A est une protobinaire ~ 600 AU



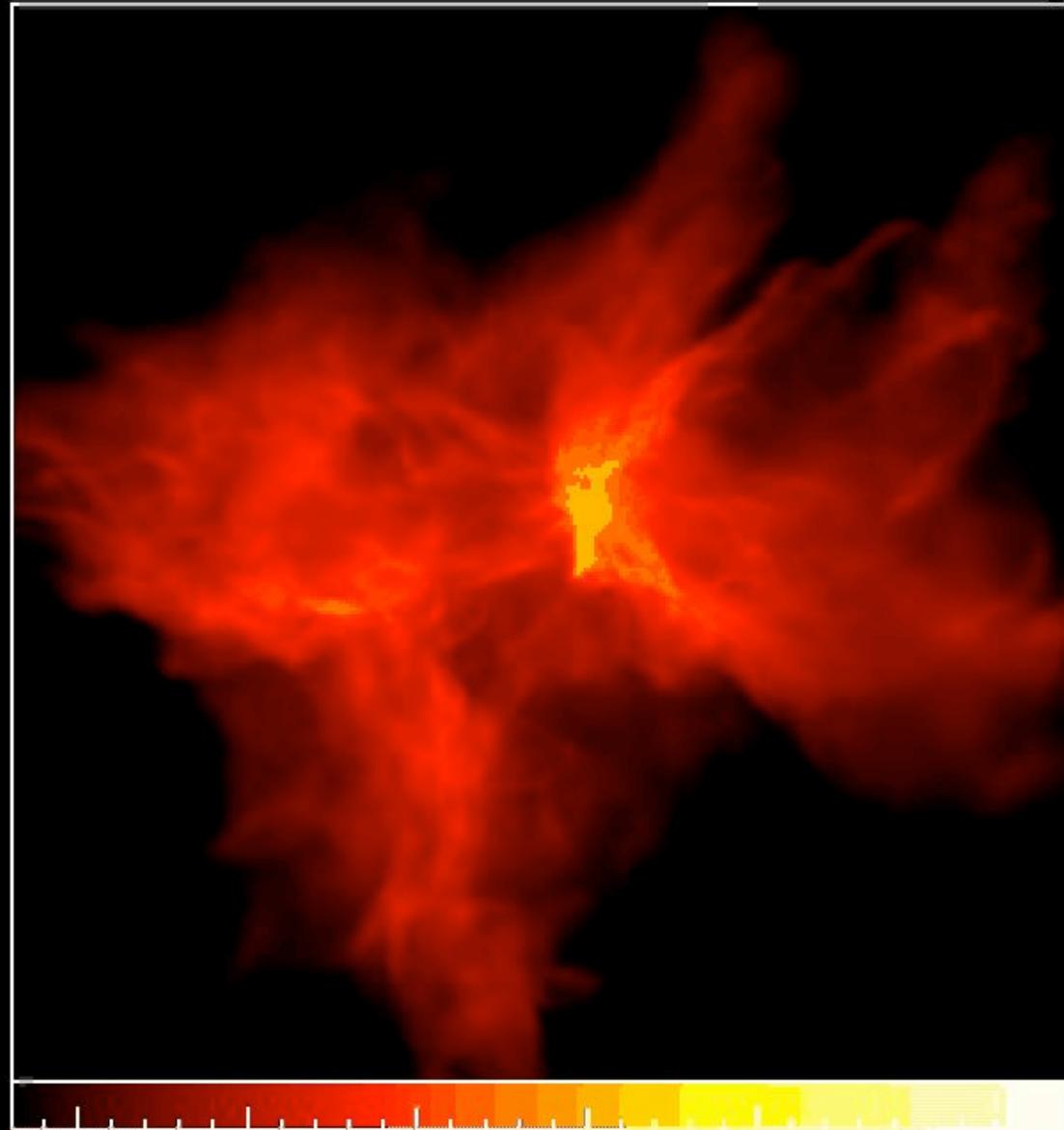
Obs. BIMA - 2.7 mm
(Looney et al. 2000)

Simulations SPH d'effondrement avec compression et rotation: Hennebelle et al. 2004



Dimensions: 82500. AU

Time: 197220. yr

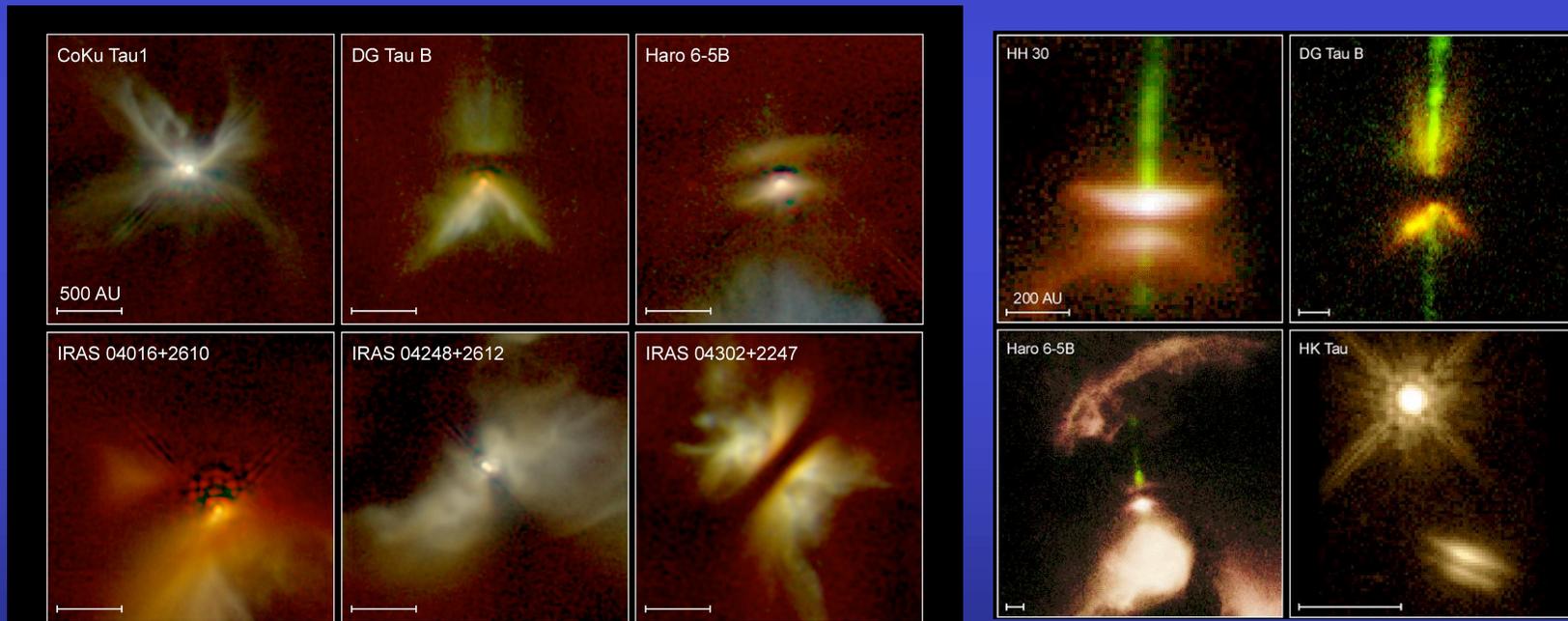


-1.5 -1.0 -0.5 0.0 0.5 1.0

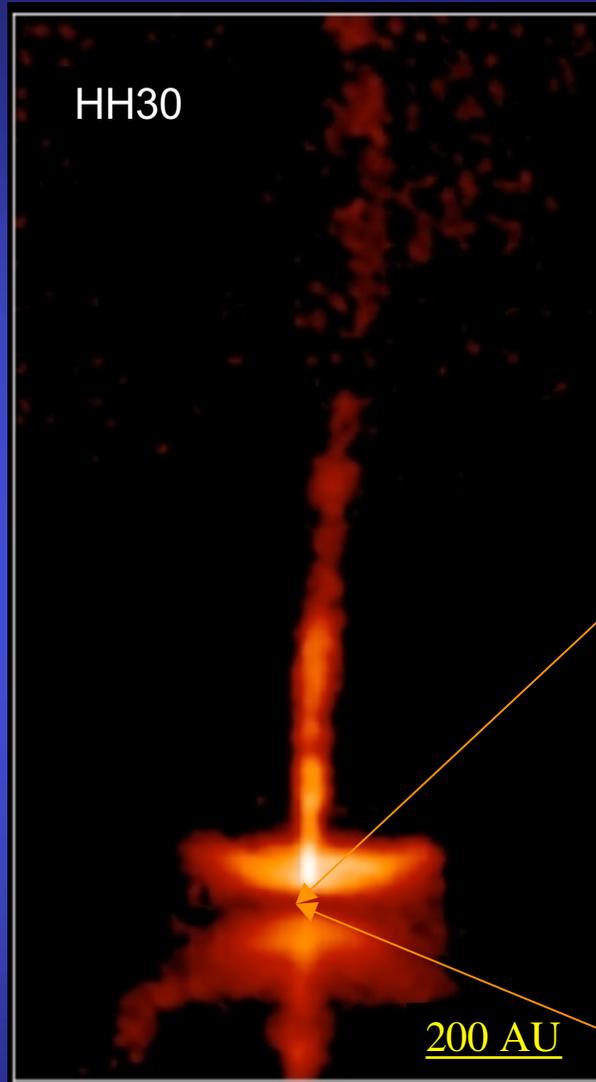
Star formation in a turbulent $\sim 50 M_{\odot}$ cloud Log Column Density [g/cm^2]

Matthew Bate (2004) Aussois (6/3/06) 14

Ubiquity -and diversity- of jets and circumstellar disks :
The "accretion-ejection" phenomenon
and the role of the (molecular) environment



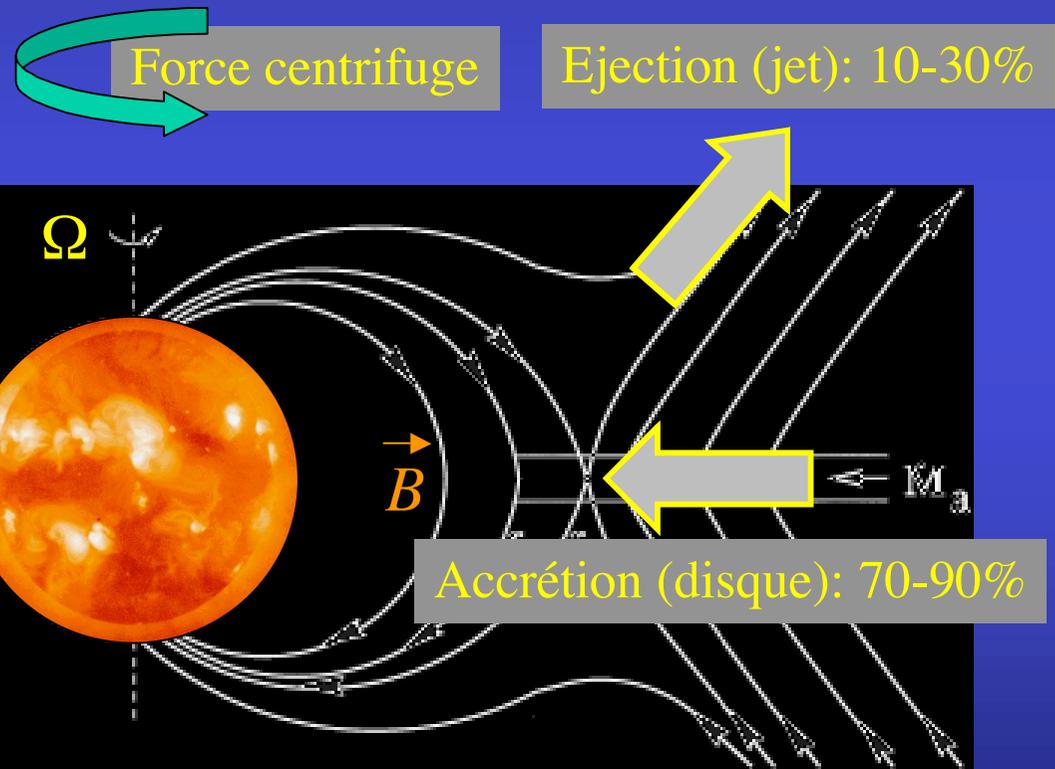
HST



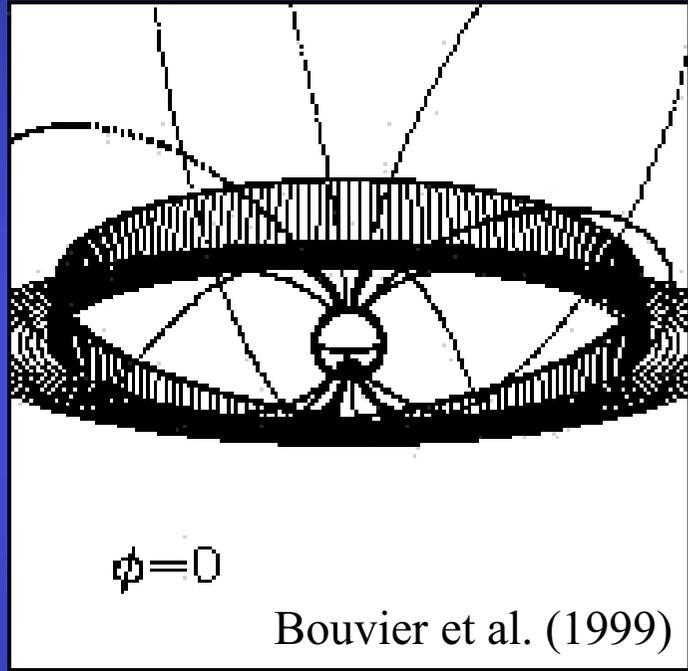
Mécanisme MHD par couplage magnétique

(J. Ferreira et al., 2001)

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

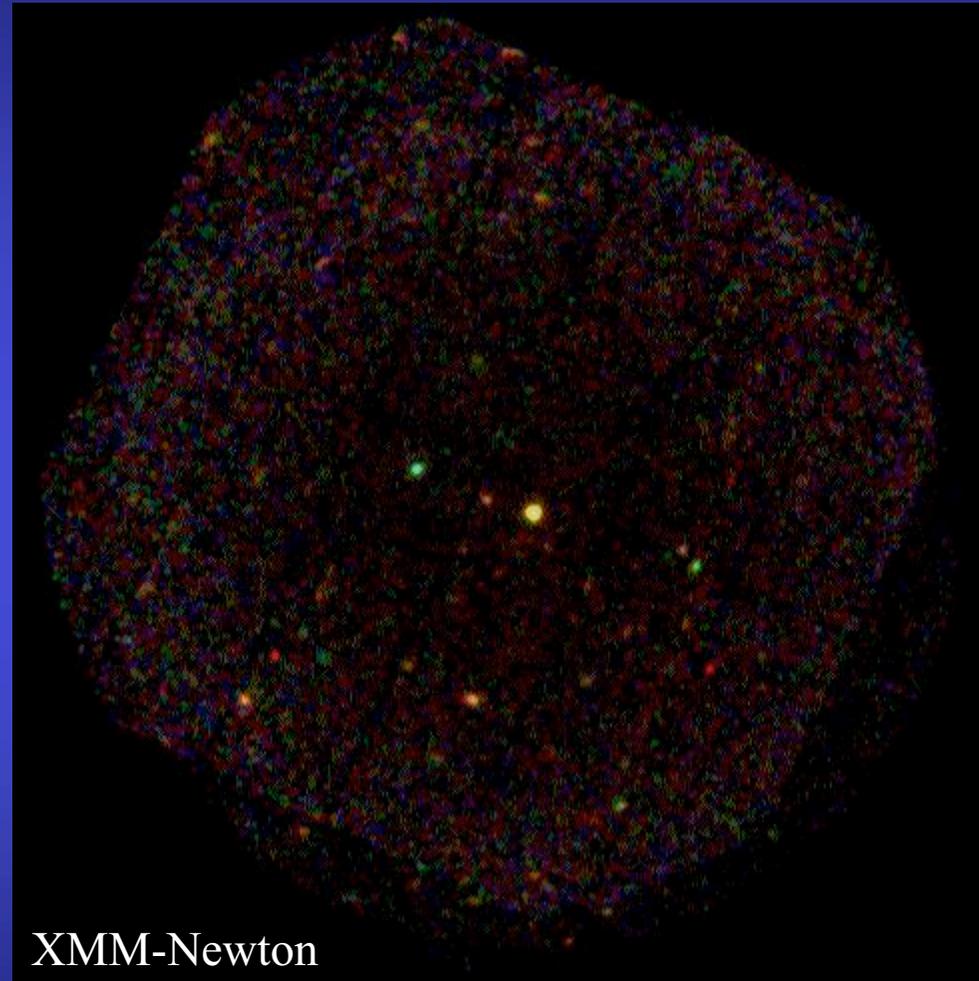


"Magnetospheric accretion": AA Tau, "Classical" T Tauri star



Magnetospheric accretion model

Rotation period ~ 1 week



XMM-Newton

0.5-1 keV

1-2.4 keV

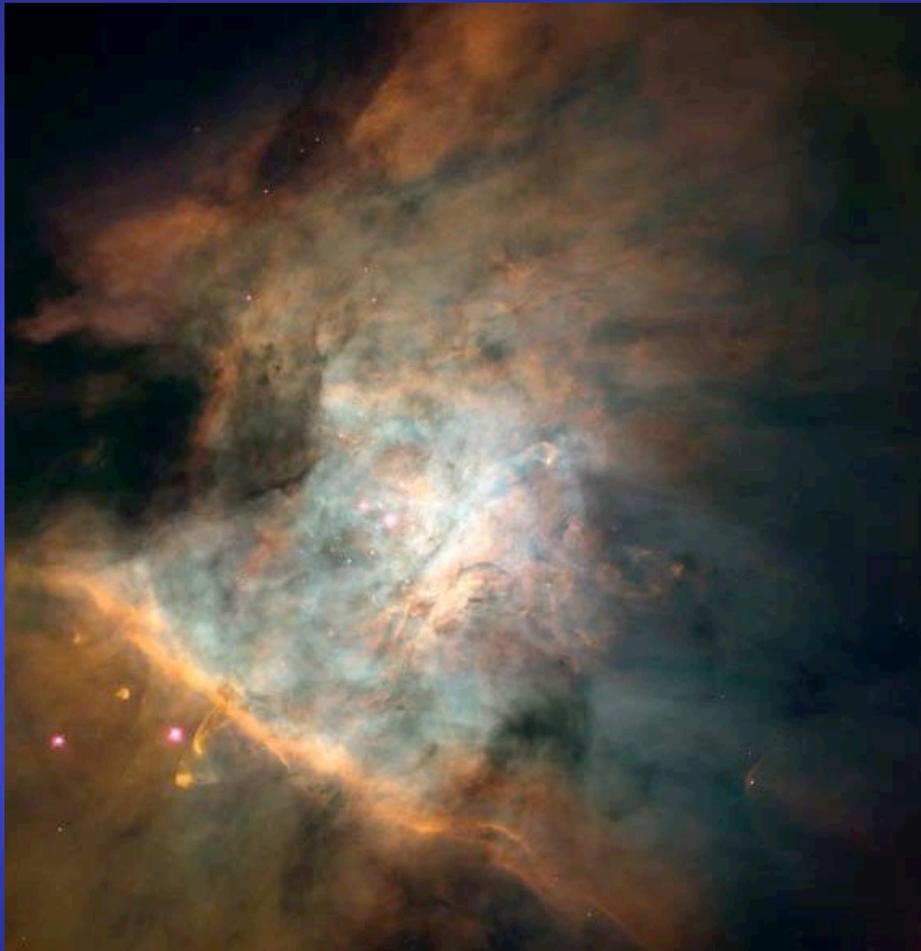
2.4-8 keV

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

2. Formation planétaire

*2.1. Stade T Tauri:
effets d'irradiation sur les disques*

Zoom dans la nébuleuse d'Orion...

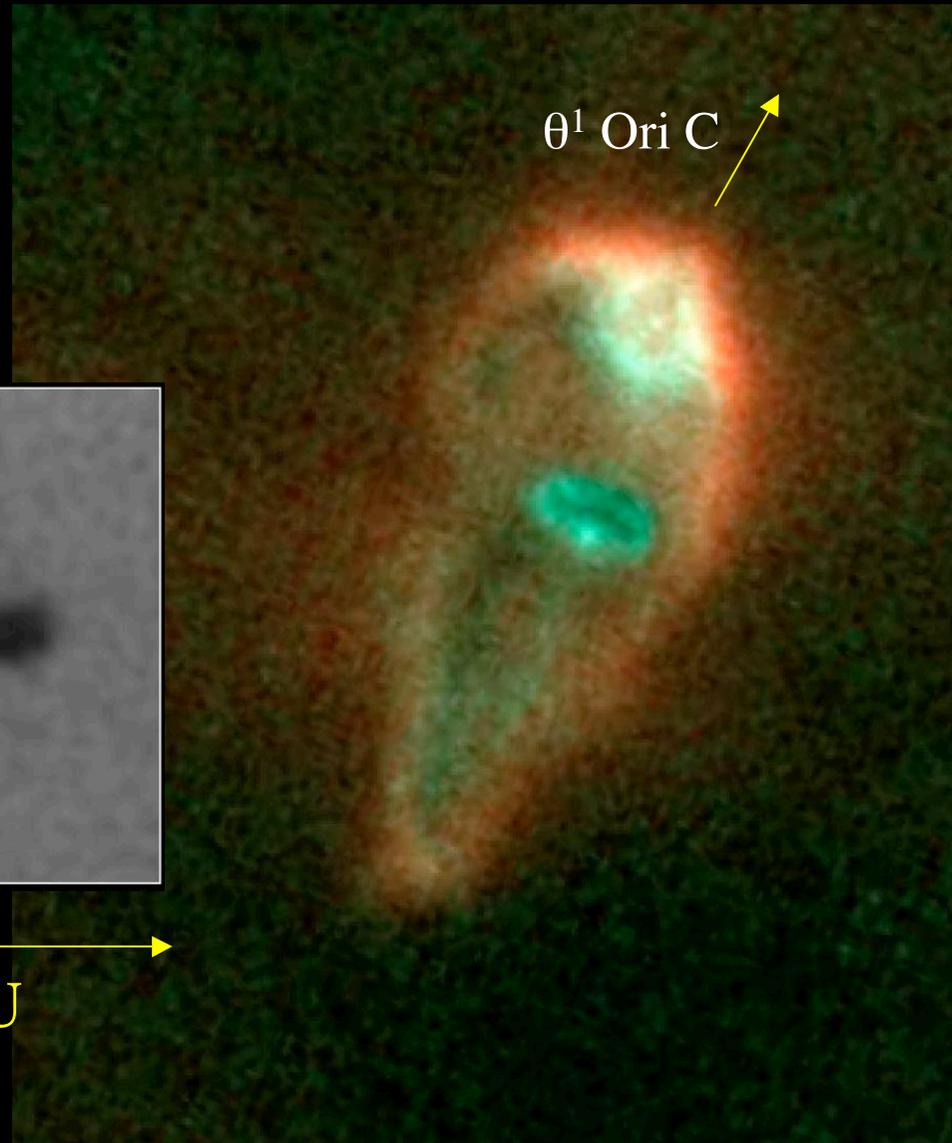


HST (Hubble)



1995

2001



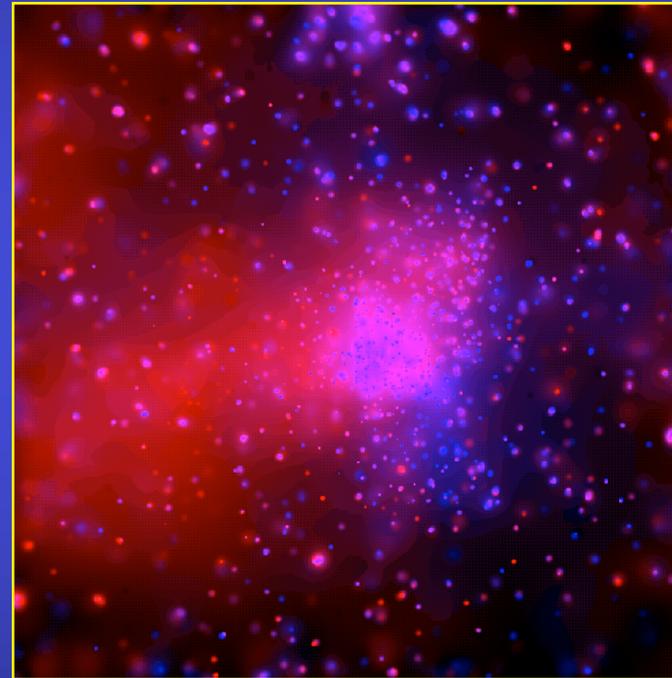
500 AU

M17, the Omega Nebula : a “hollow”, hot HII region

2MASS (near-IR: 2 μ m)



Chandra (X-rays: 0.5-10 keV; 10^6 - 10^7 K)

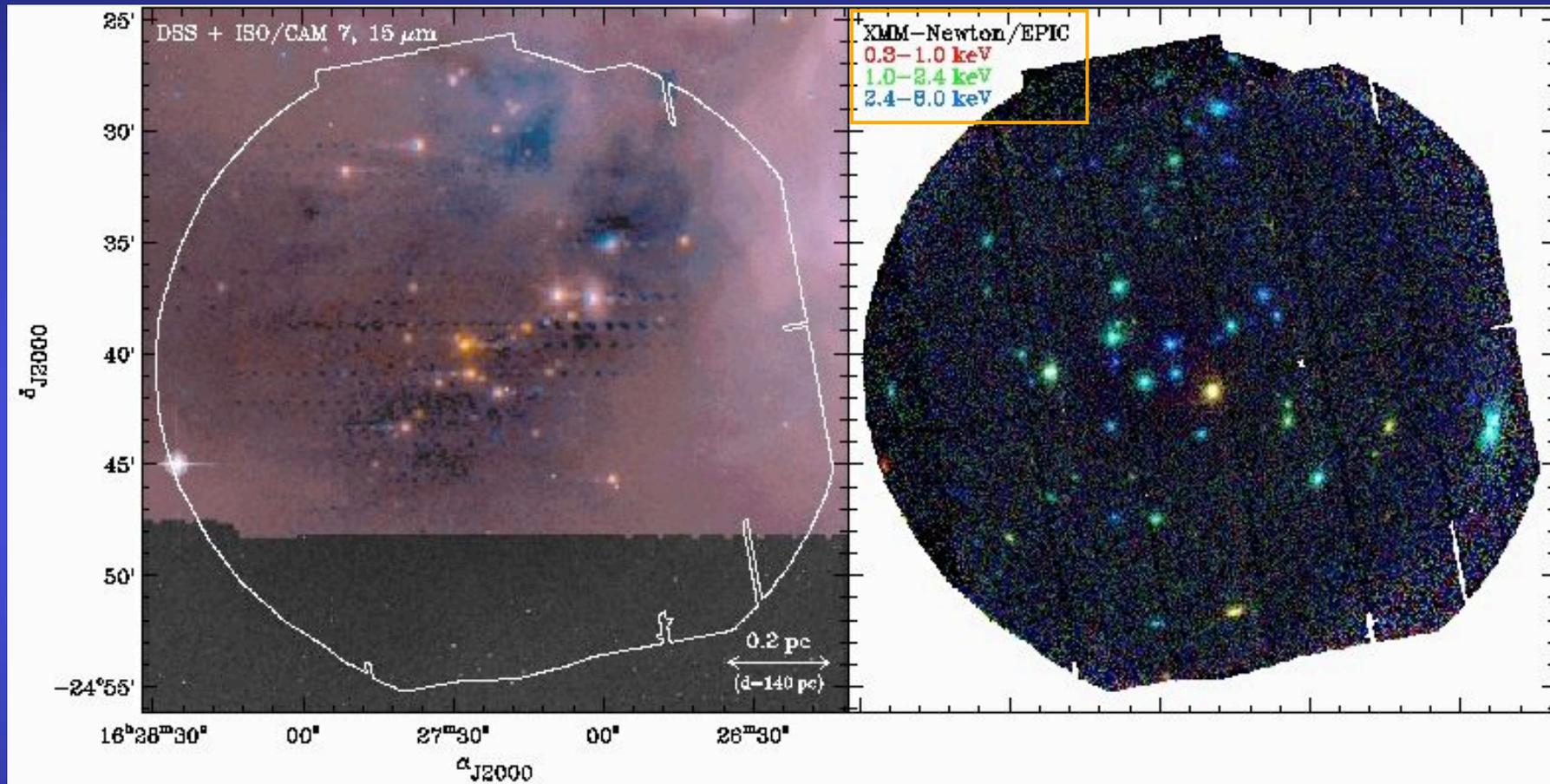


$d \sim 2$ kpc, ≥ 13 O (O3 \rightarrow O9.5) + 34 B + x 1000 T Tauri stars

X-ray bubble blown by O-star winds, heated by strong shocks

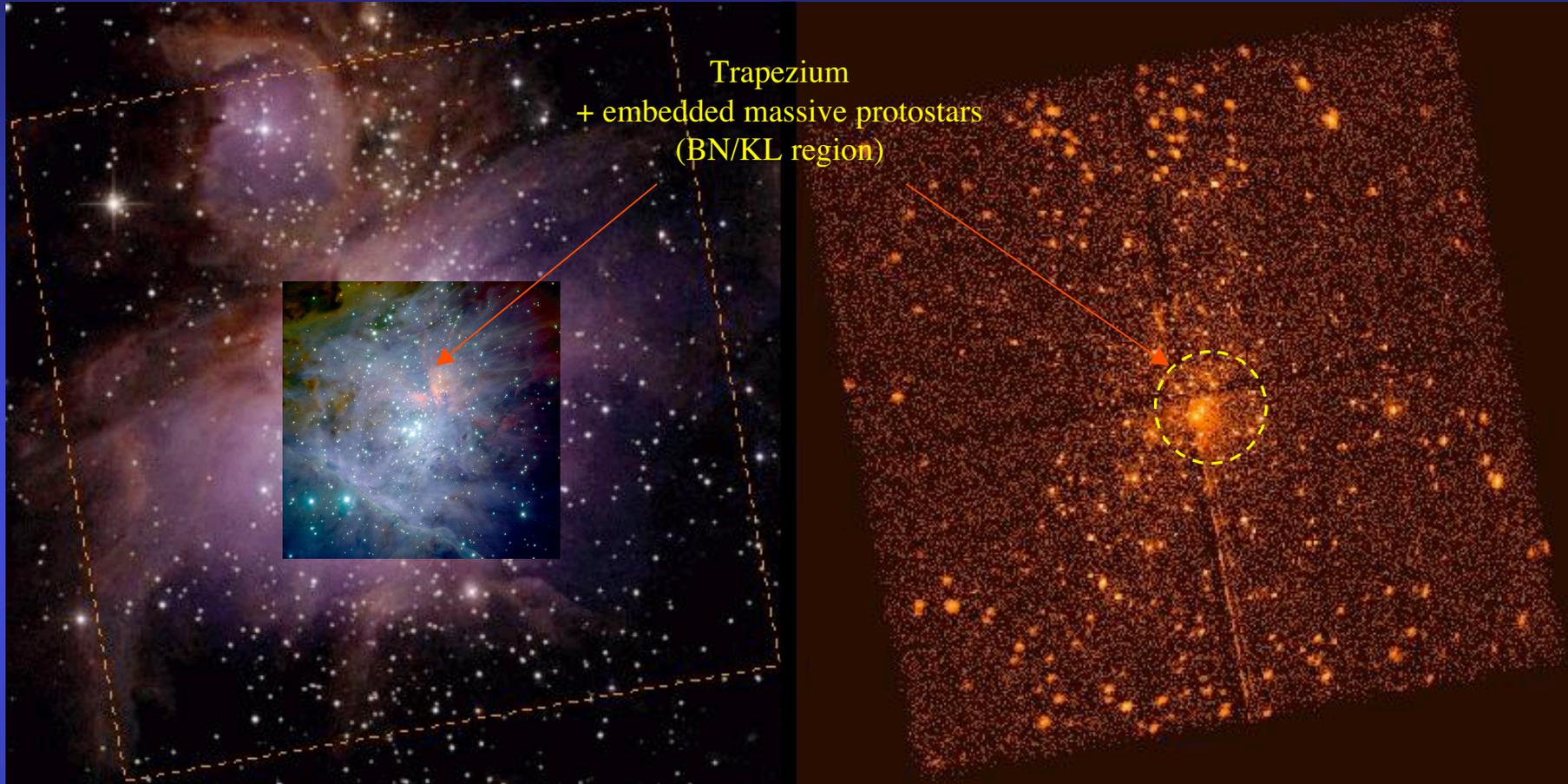
(Townsend, Montmerle, et al. 2003, ApJ)

"Local" irradiation by the central star: The X-ray/IR connection



The XMM view of the ρ Oph cloud core
(Ozawa, Grosso, Montmerle 2004, *A&A*)

High-mass star forming regions



Near-IR image (2MASS + VLT)

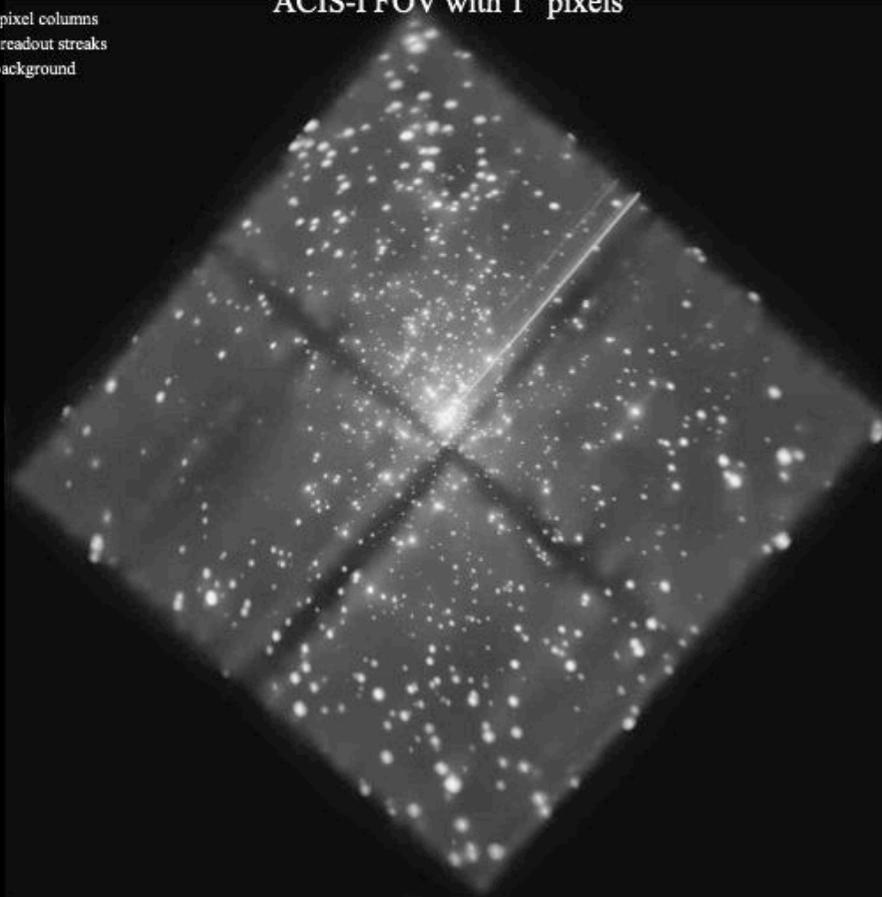
X-ray image (*Chandra* ACIS-I): Garmire et al. 2000

Orion Nebula (M42) and Trapezium region, O7+ ($\sim 17' \times 17'$)

~ 1600 sources, $L_X \sim 10^{28} - 10^{32} \text{ erg s}^{-1}$ ($\sim 10 - 10^5 L_{X,\odot}$)

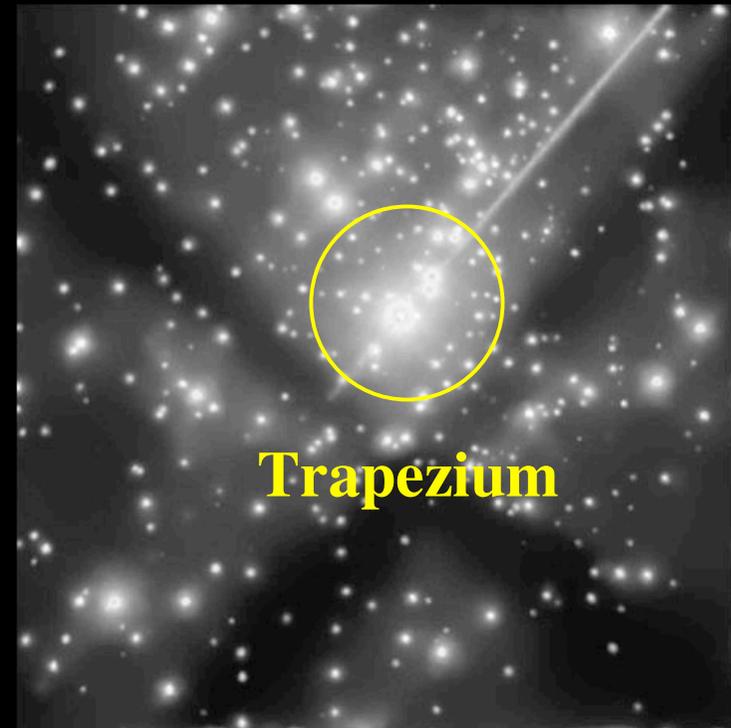
- ❖ Chip gaps and bad pixel columns
- ❖ Pileup sources and readout streaks
- ❖ Spatially variable background

ACIS-I FOV with 1" pixels



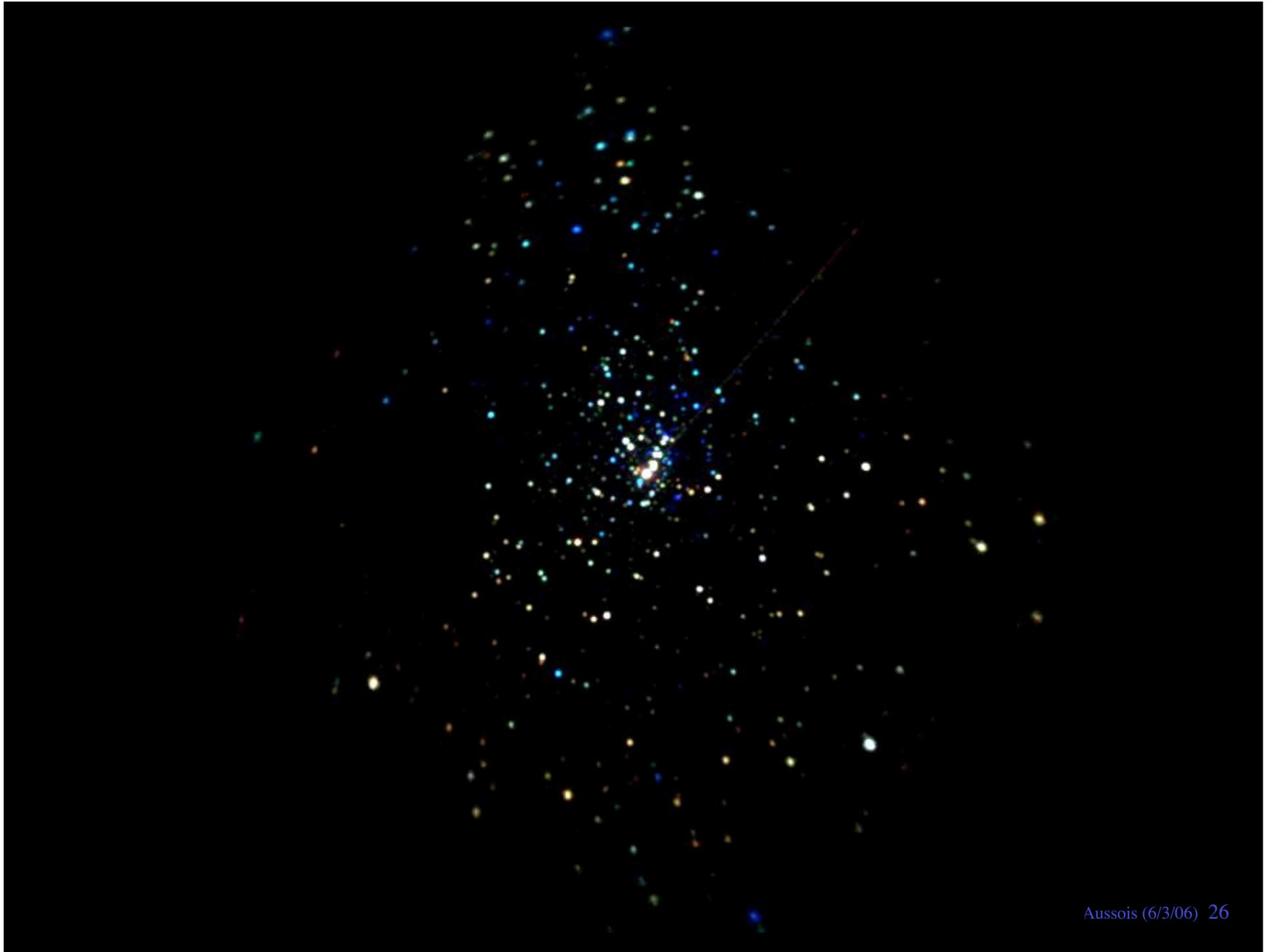
n (1.7-2.8); blue (2.8-8.0)

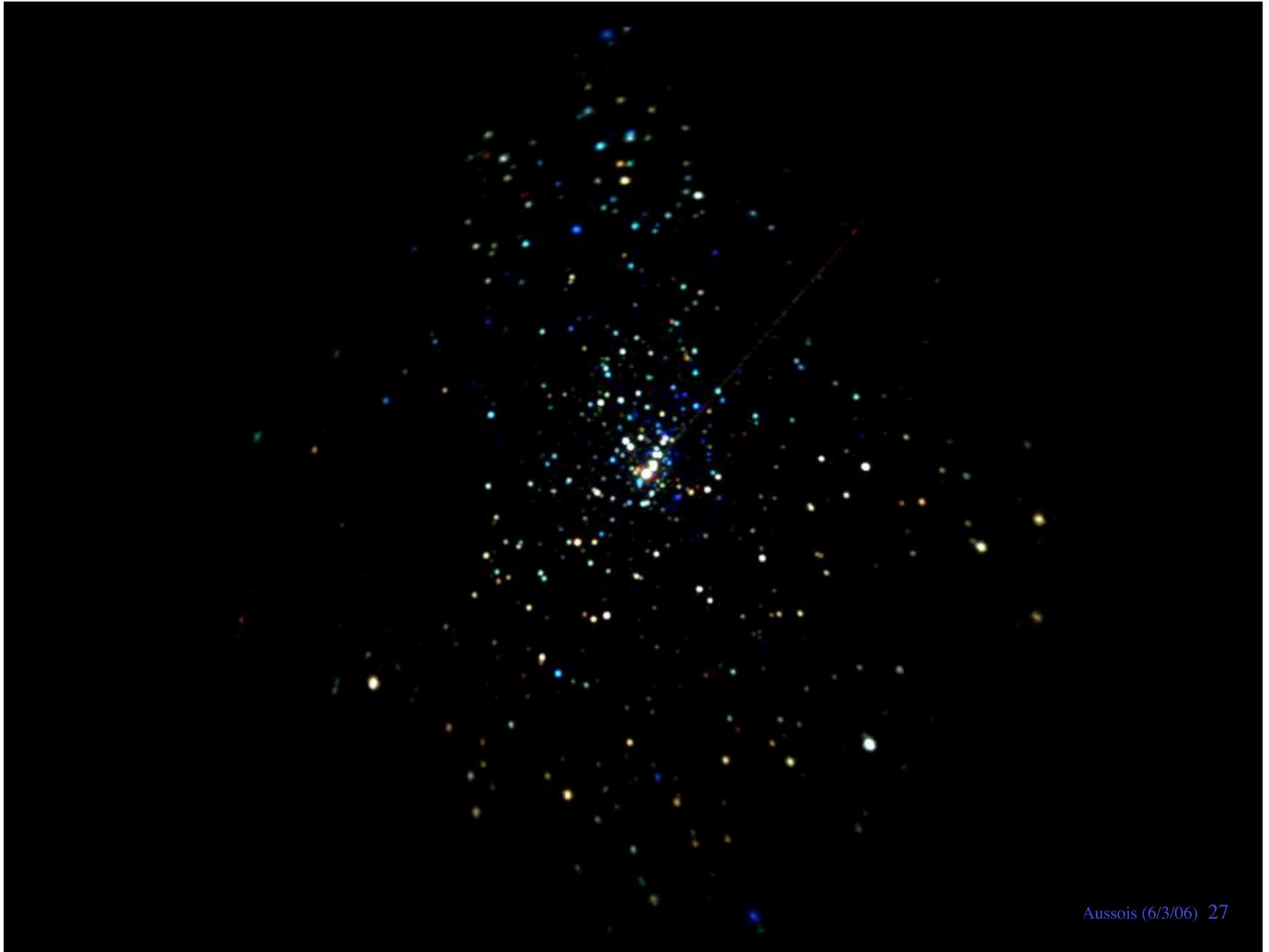
Central ACIS-I region with 0.25" pixels



Trapezium

“COUP” = *Chandra Orion*
Ultradeep Project = 10 days exp.
Jan. 2004 (PI E.D. Feigelson)





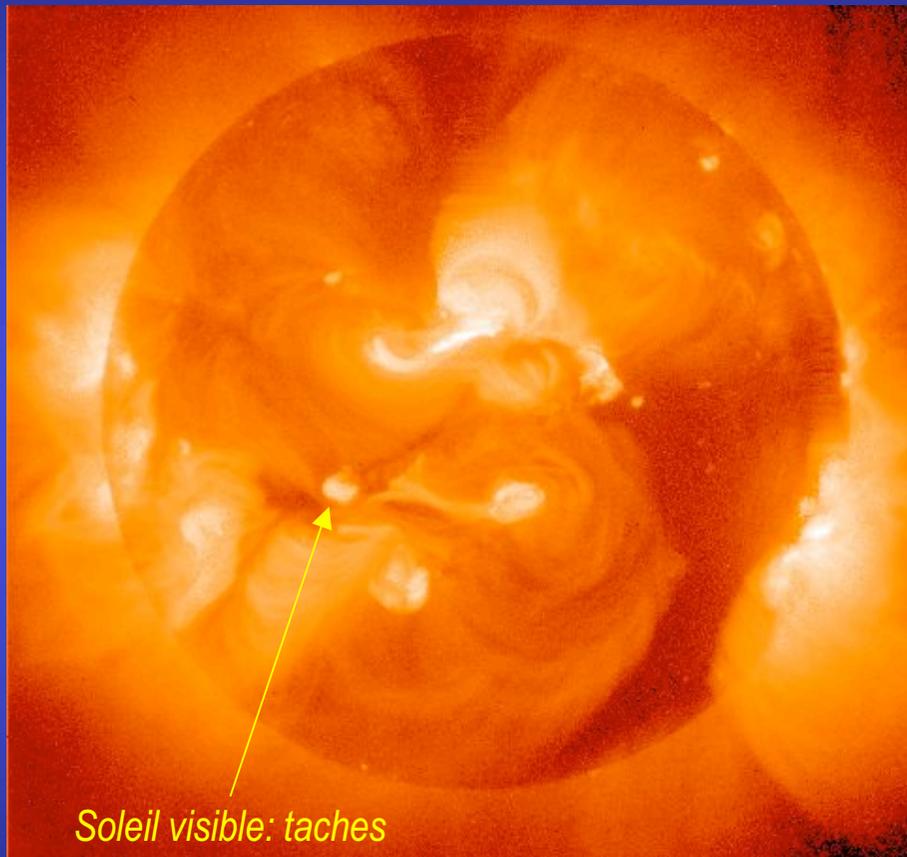


X-ray: Chandra/ACIS/Feigelson et al. (COUP)

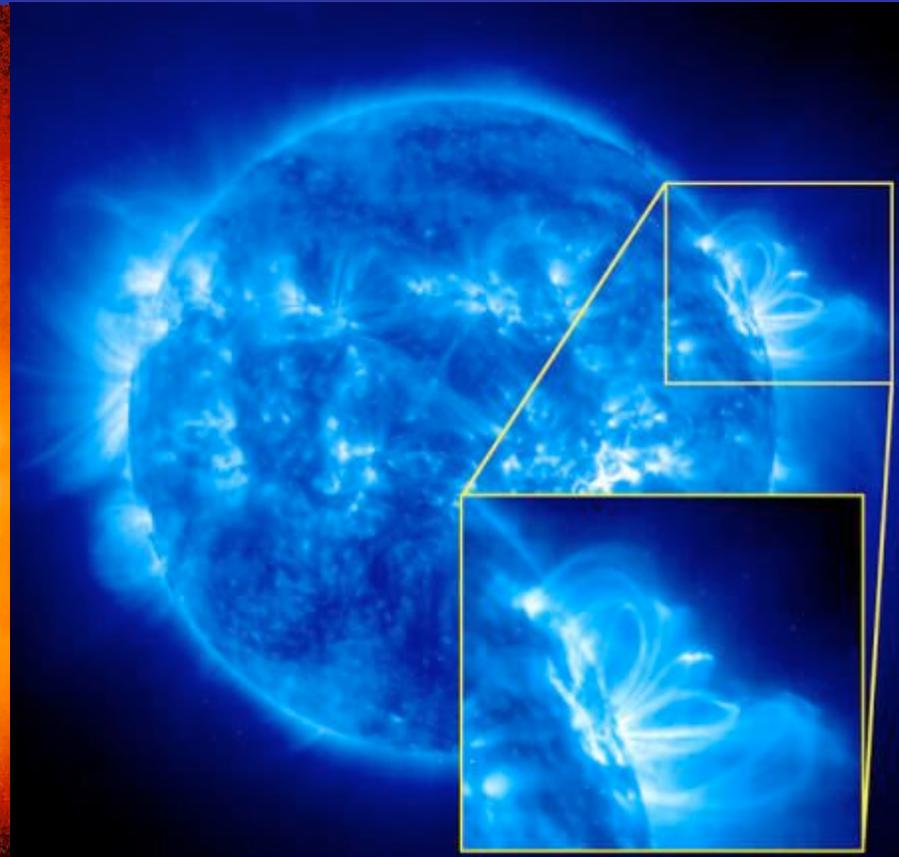
Infrared: VLT/ISAAC/McCaughrean et al.

ssois (6/3/06) 28

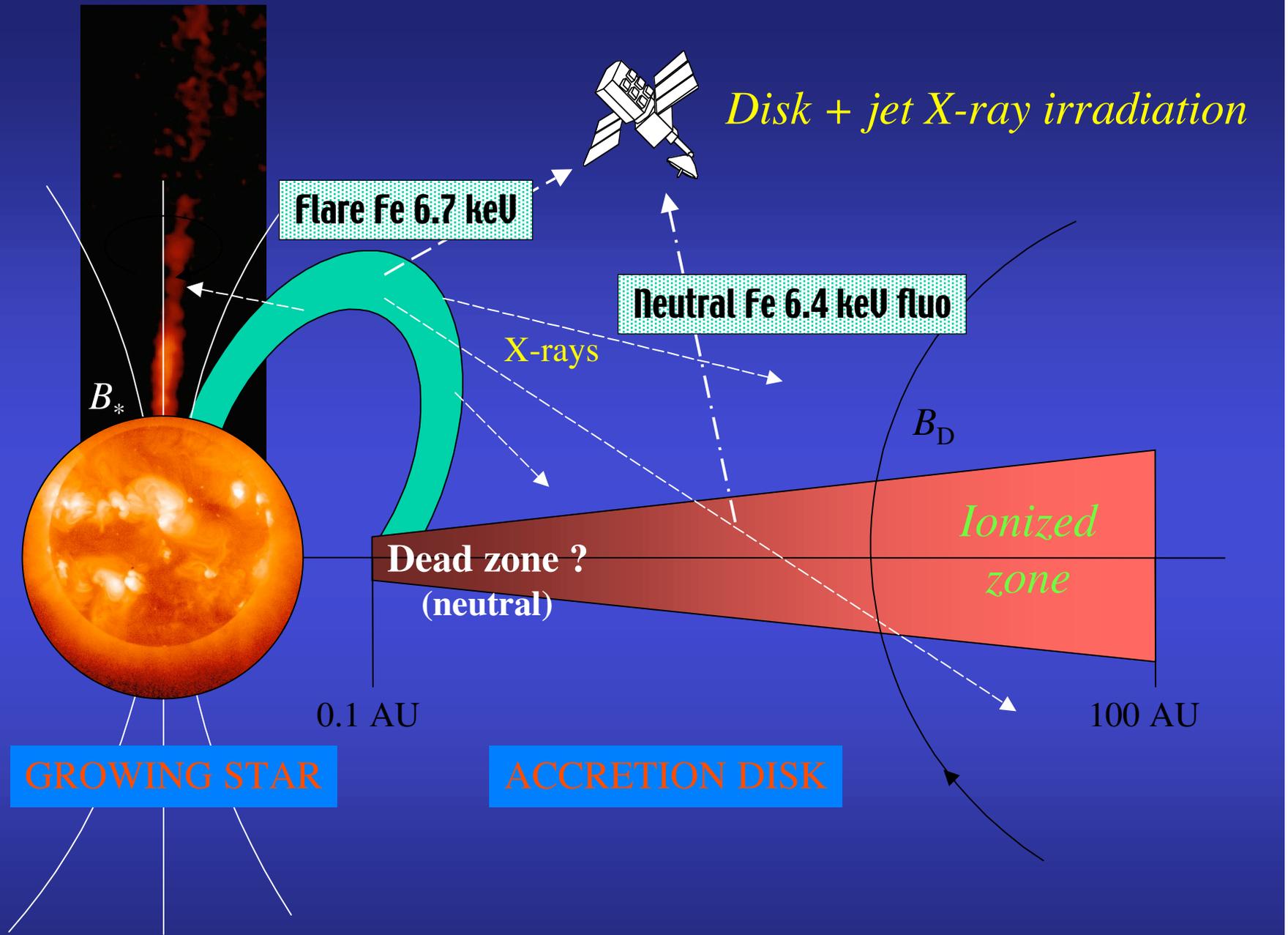
Les étoiles jeunes d'Orion: des "super-Soleils" ($\times 10^3$ - 10^4)



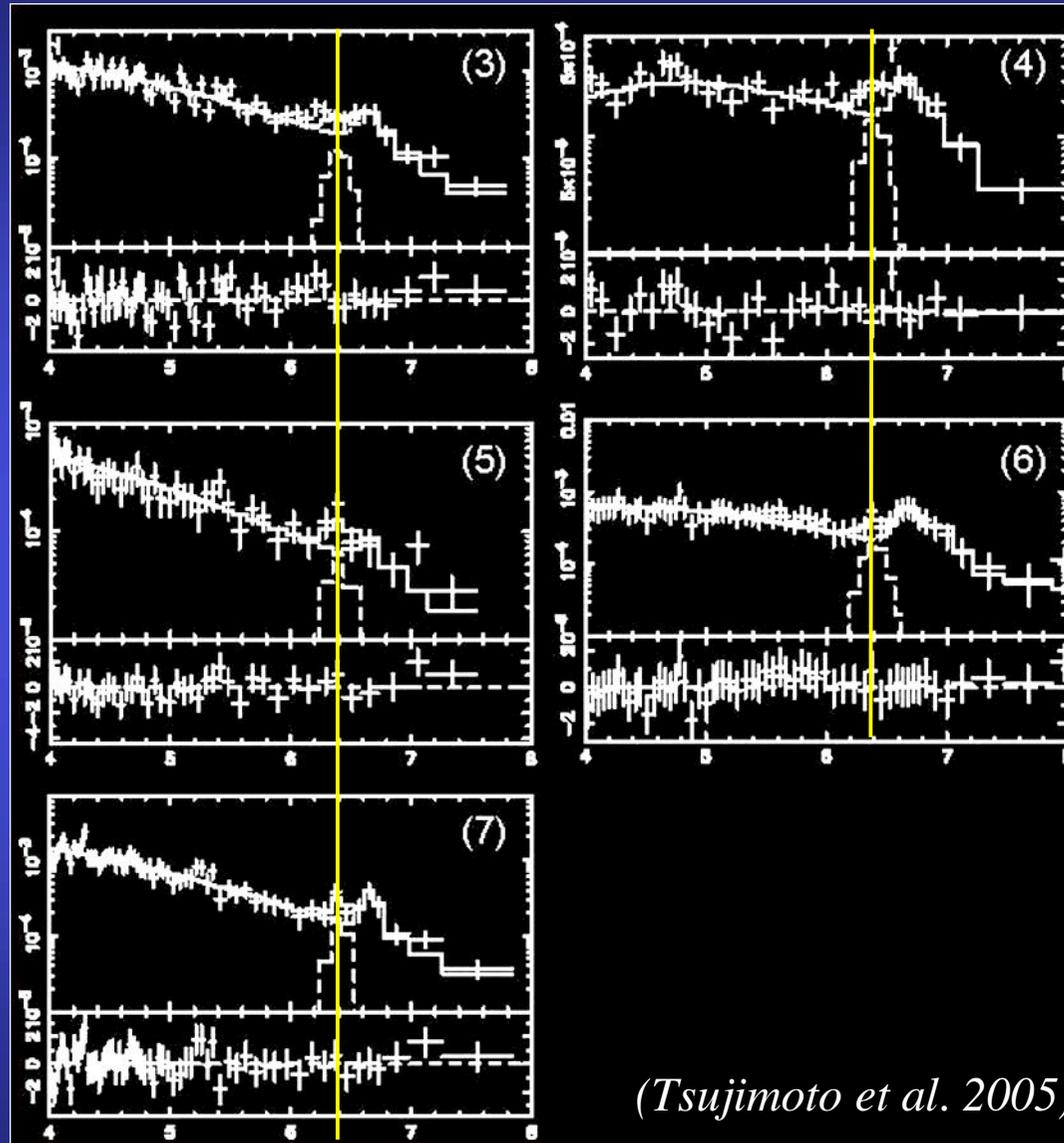
Soleil X (satellite Yohkoh)



Soleil EUV (satellite SOHO)



The Magnificent Seven: fluorescing sources in Orion...



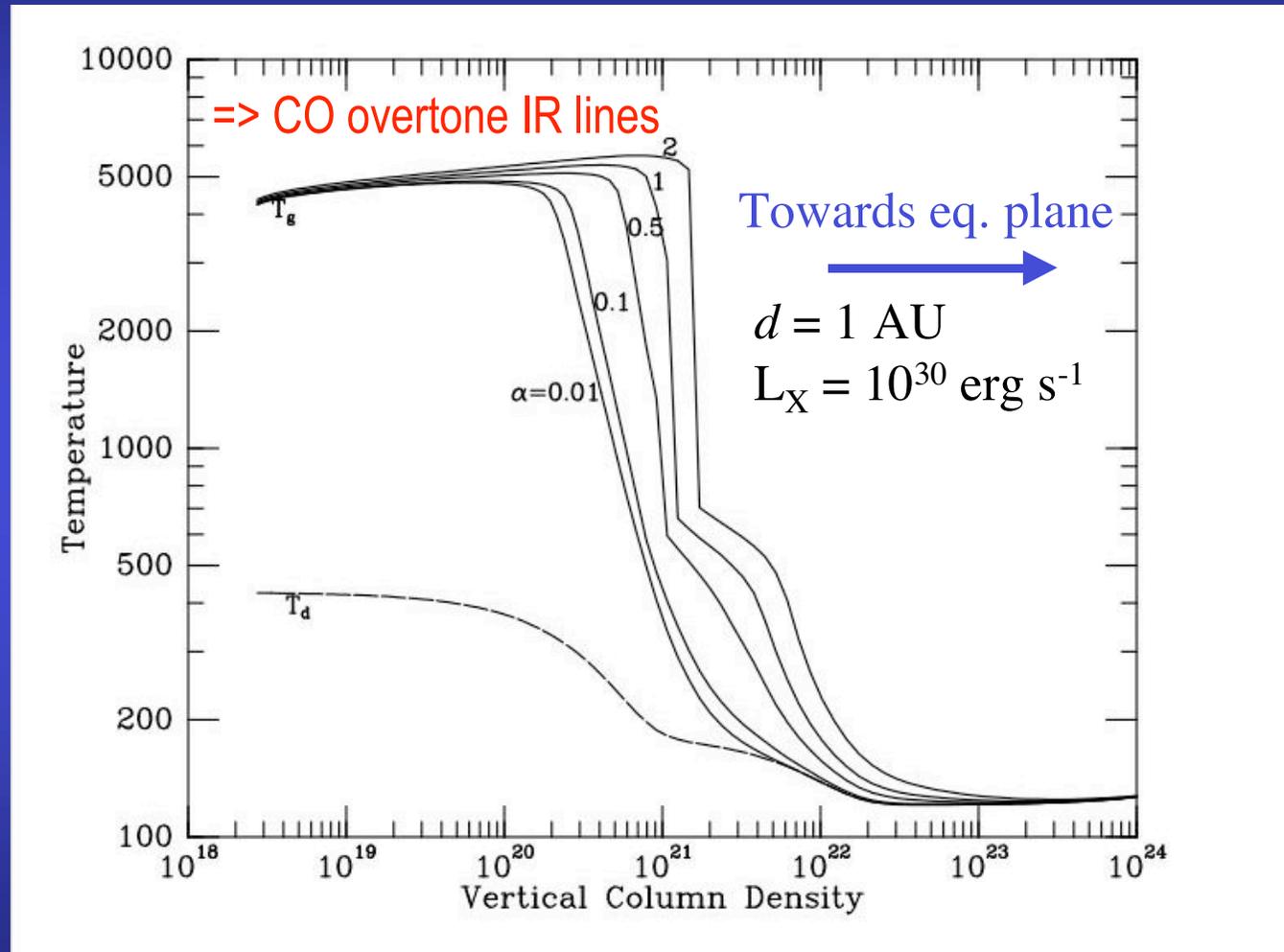
See also E129
(Cl. I) in ρ Oph
(Favata et al. 2004)

(Tsujiimoto et al. 2005)



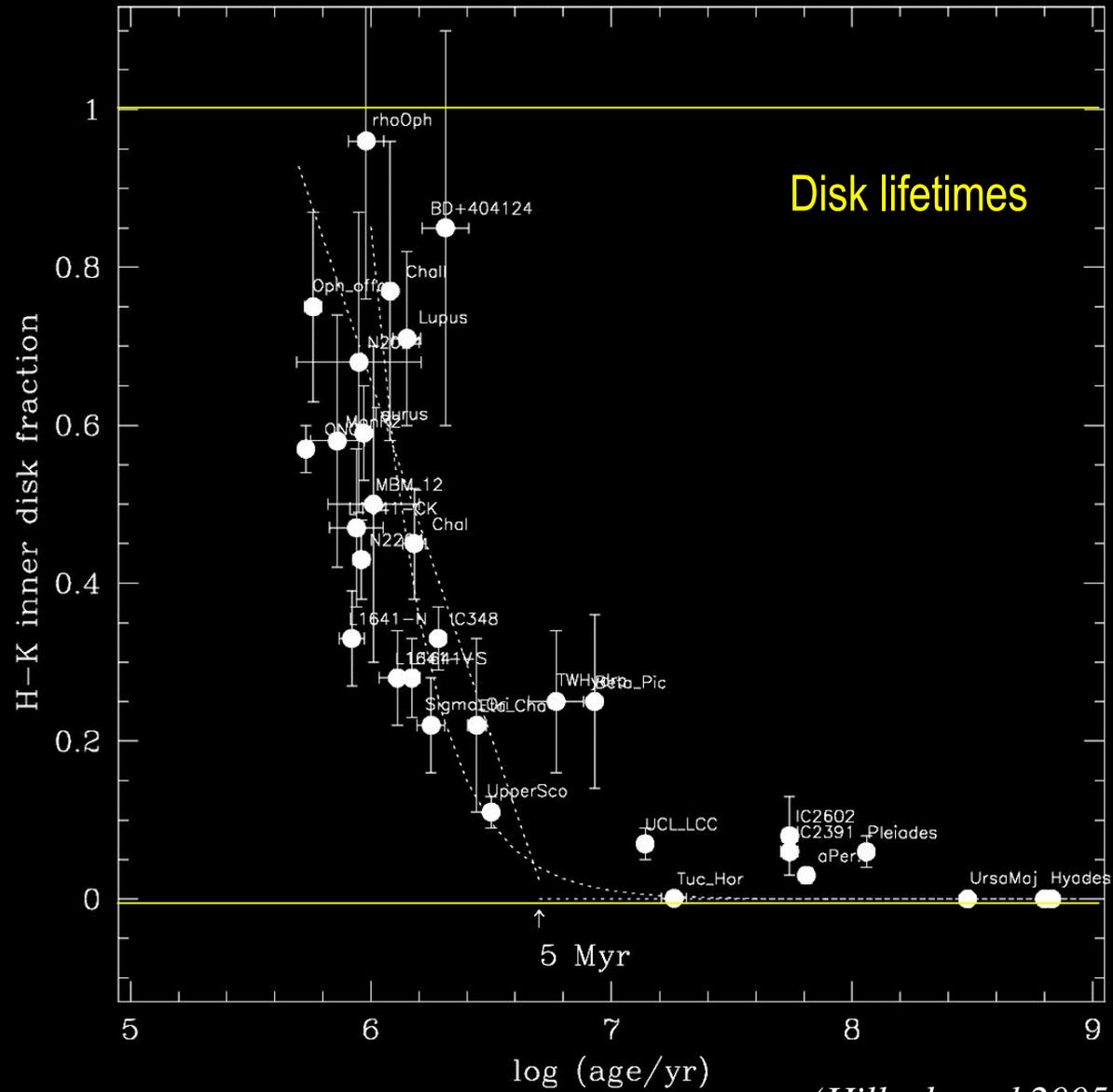
Line @ 6.4 keV \Rightarrow Direct evidence for disk irradiation

X-ray heating of the outer layers of circumstellar disks

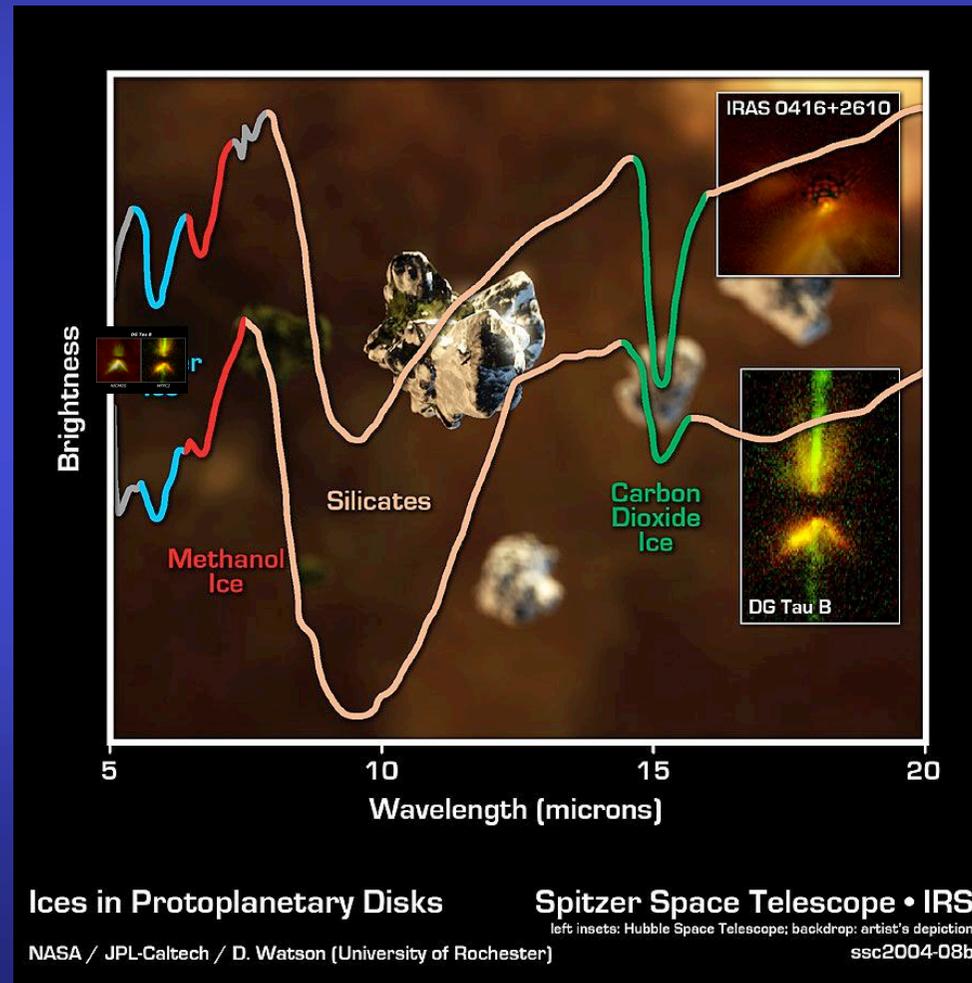
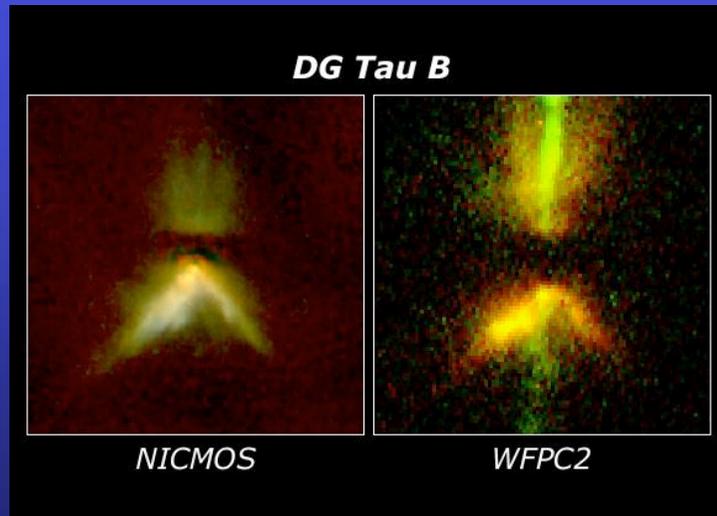
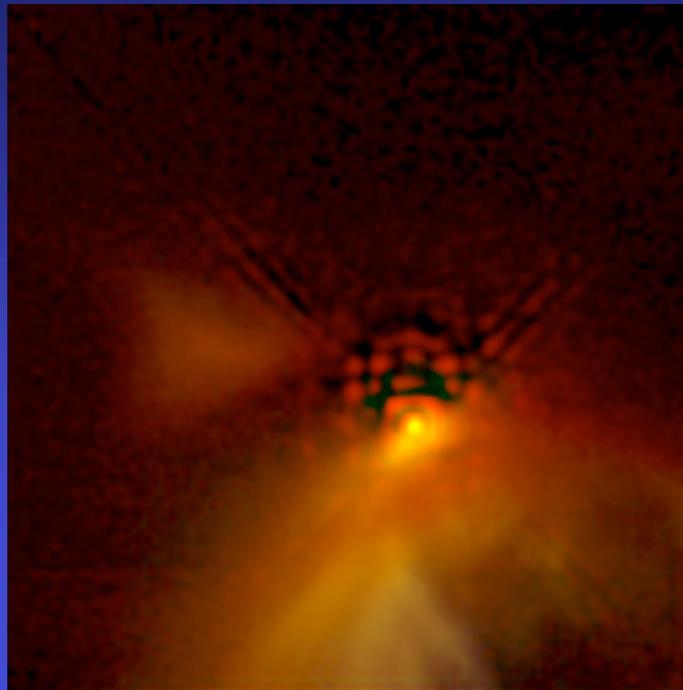


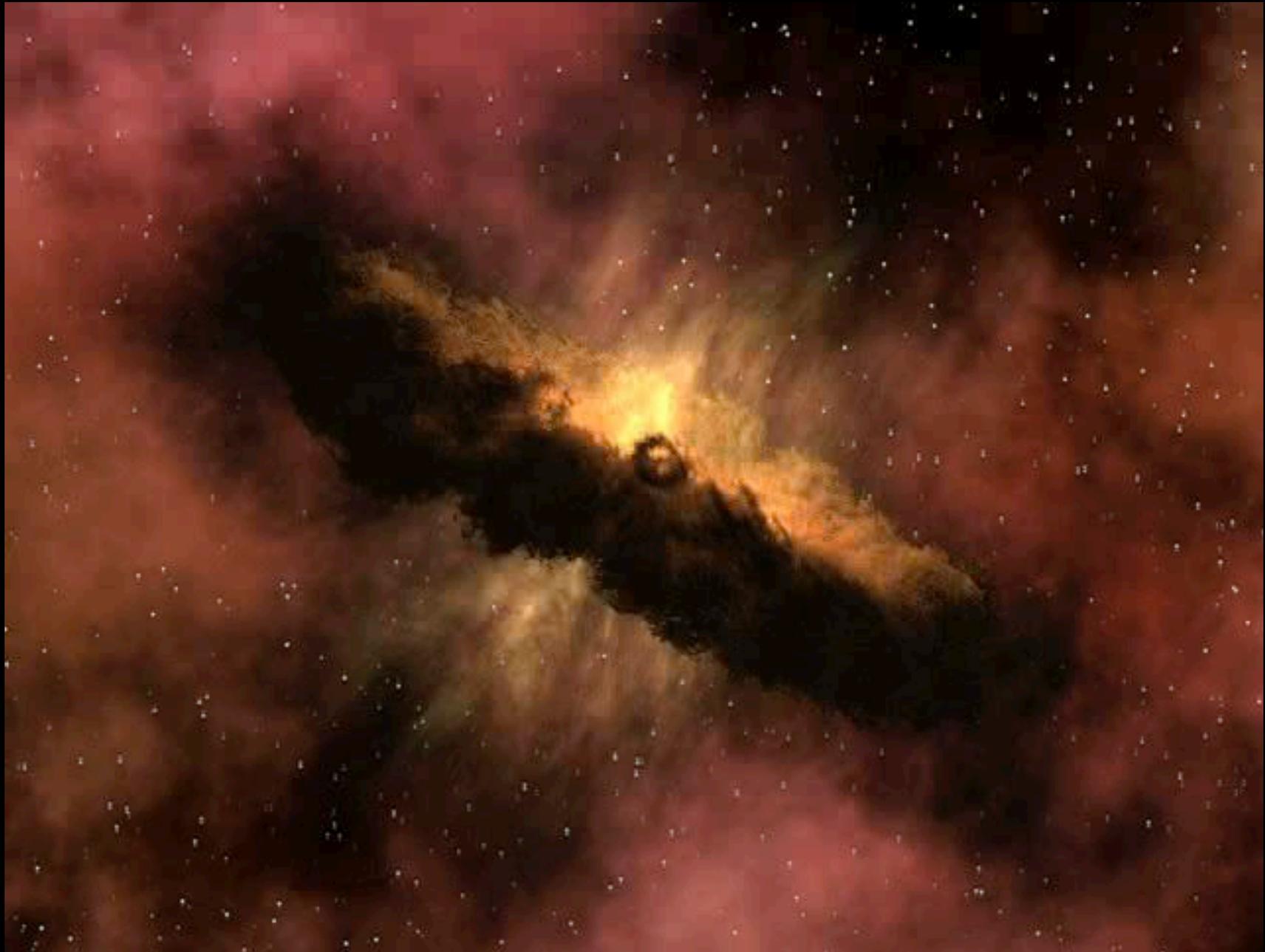
(Glassgold, Feigelson, Montmerle, Wolk 2005)

2.2 Stade T Tauri: évolution des disques

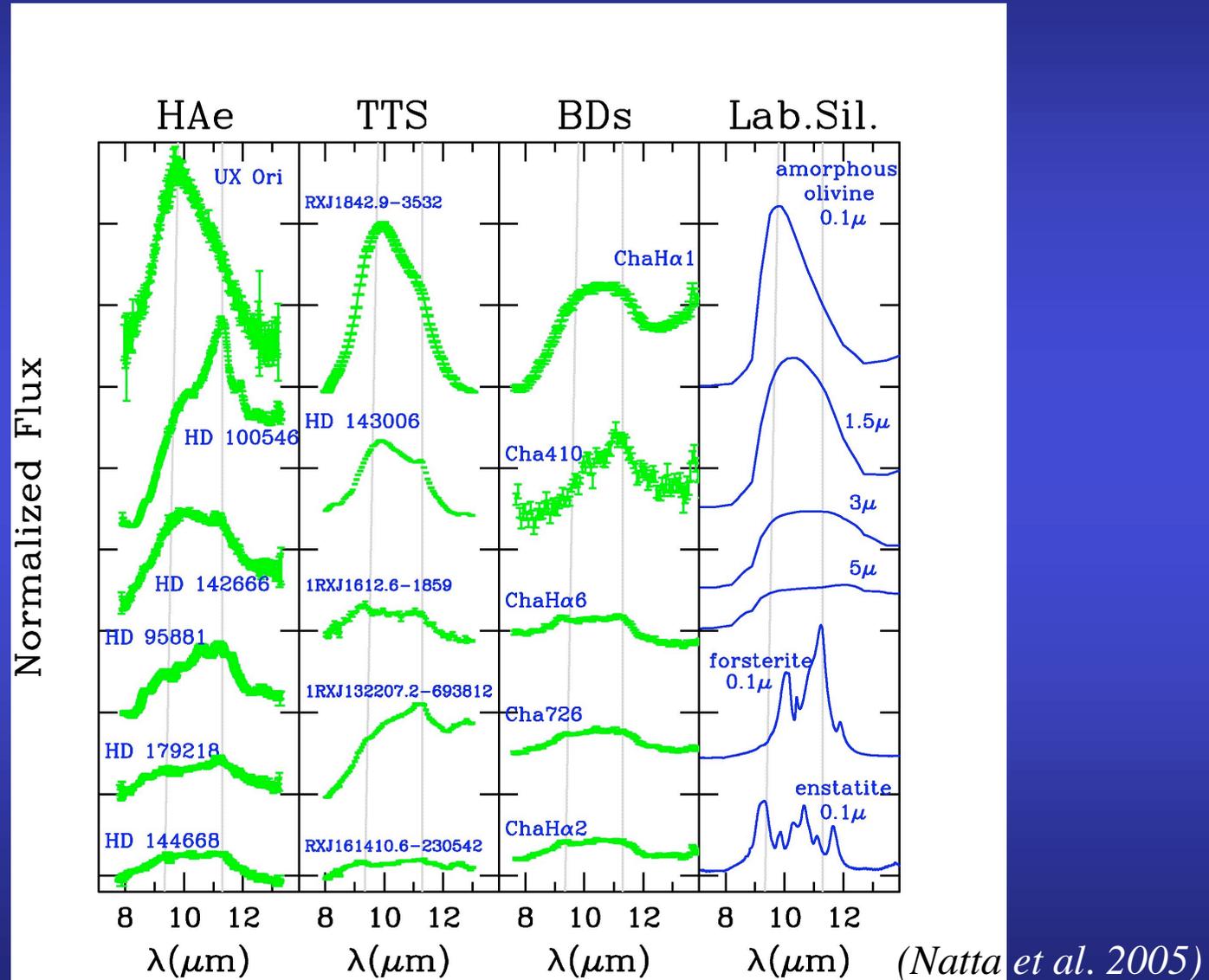


Spectres IR: minéralogie des disques



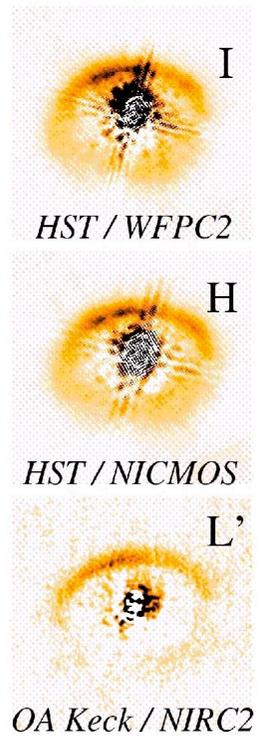


Spitzer Spectra of circumstellar disks

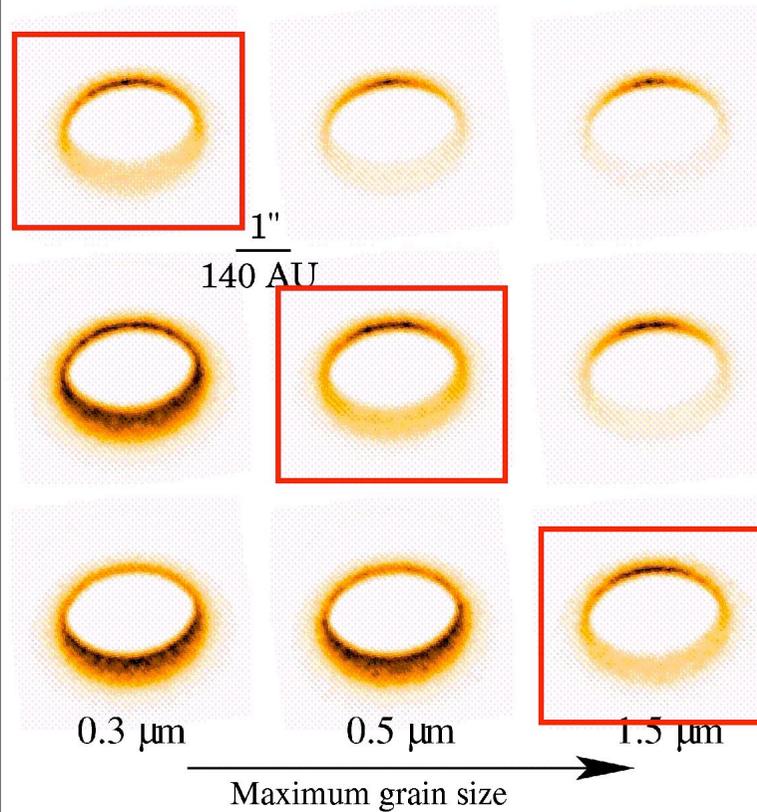


GG Tau

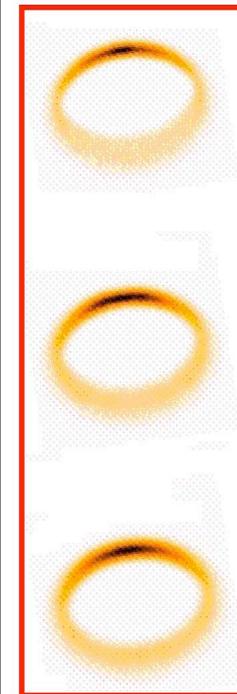
Observations



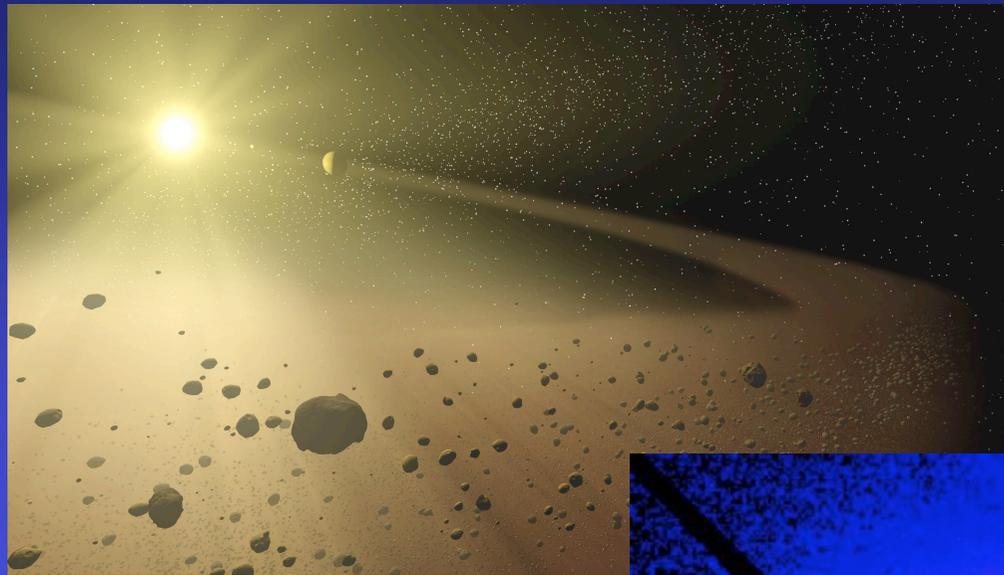
Models without dust settling



Models with dust settling

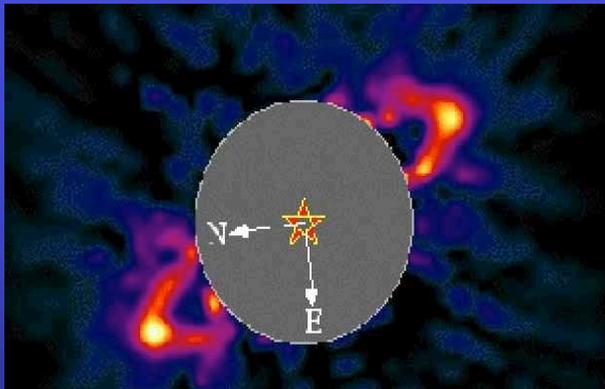


(Duchêne et al. 2004)

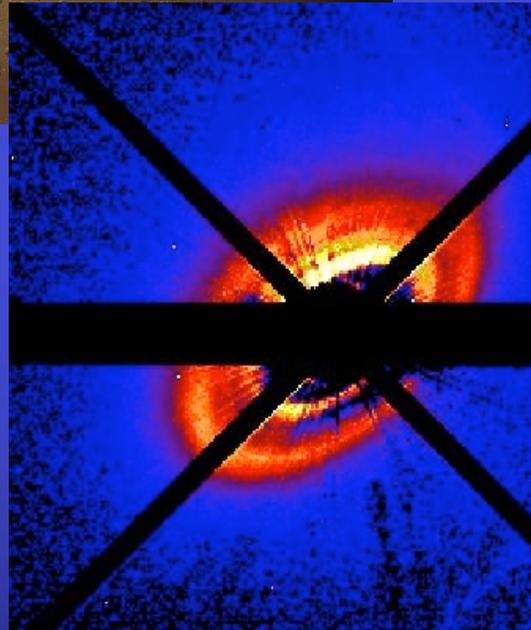


Des planètes (géantes) à la pelle...

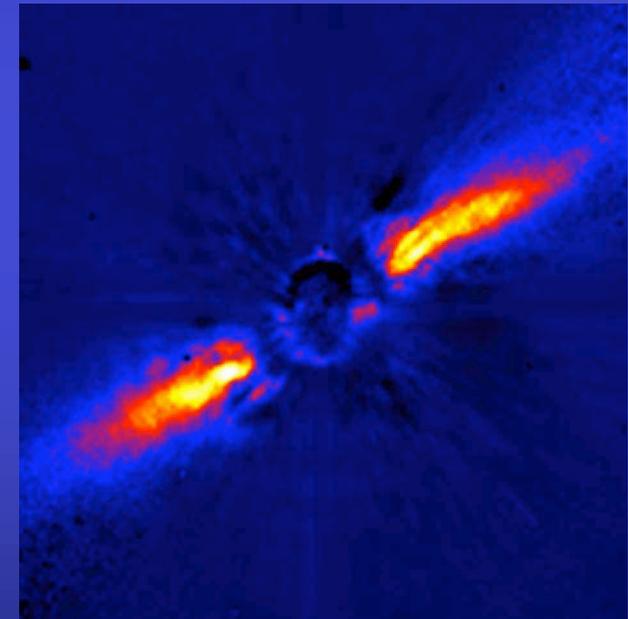
Disques évolués: « planétaires »,
ou « de débris »
(coronographie)



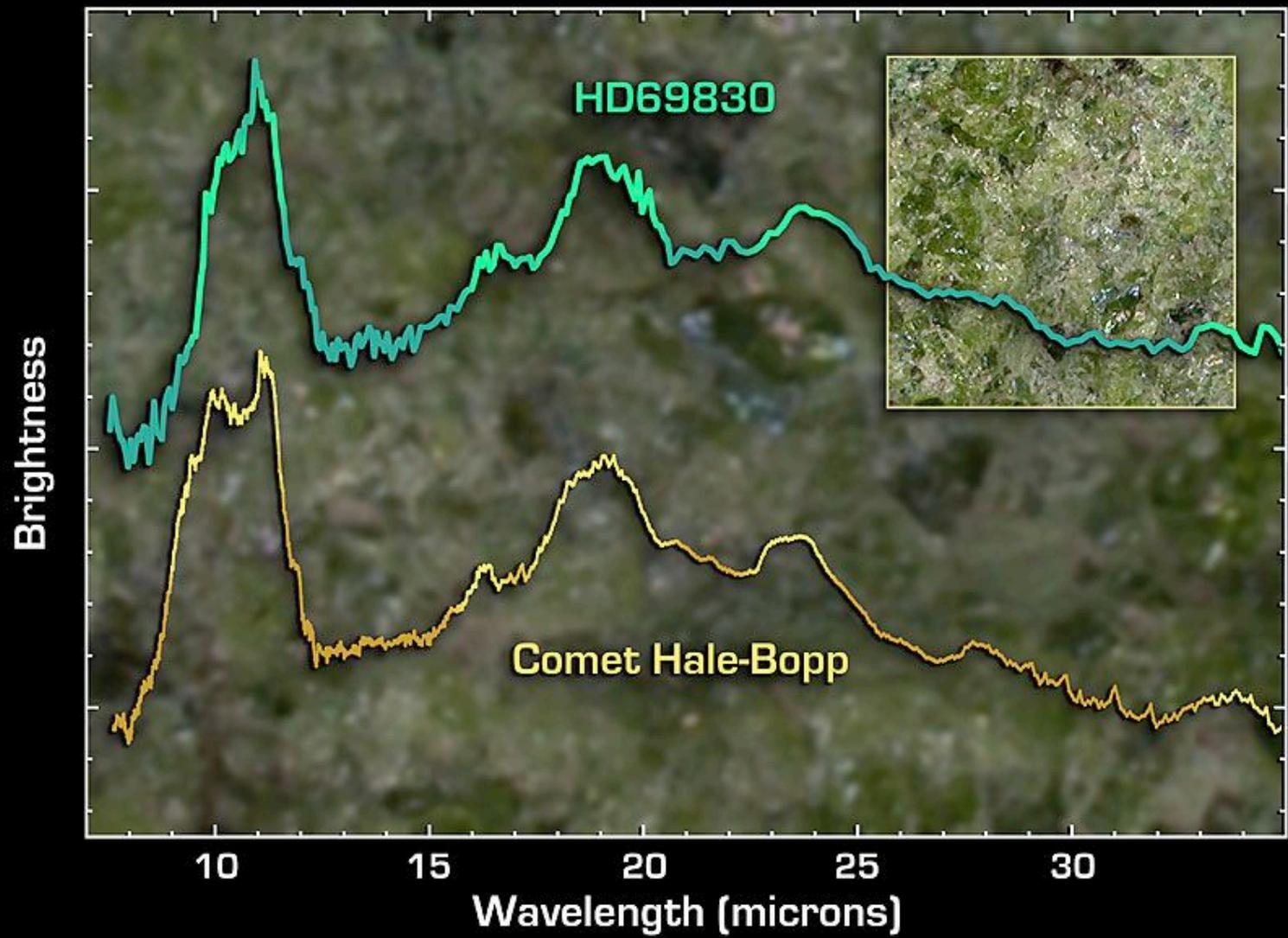
Hubble Space Telescope
(HST)



Mouillet et al. (1999)
HST



Lagrange et al. (1997)
ESO 3,60m + ADONIS



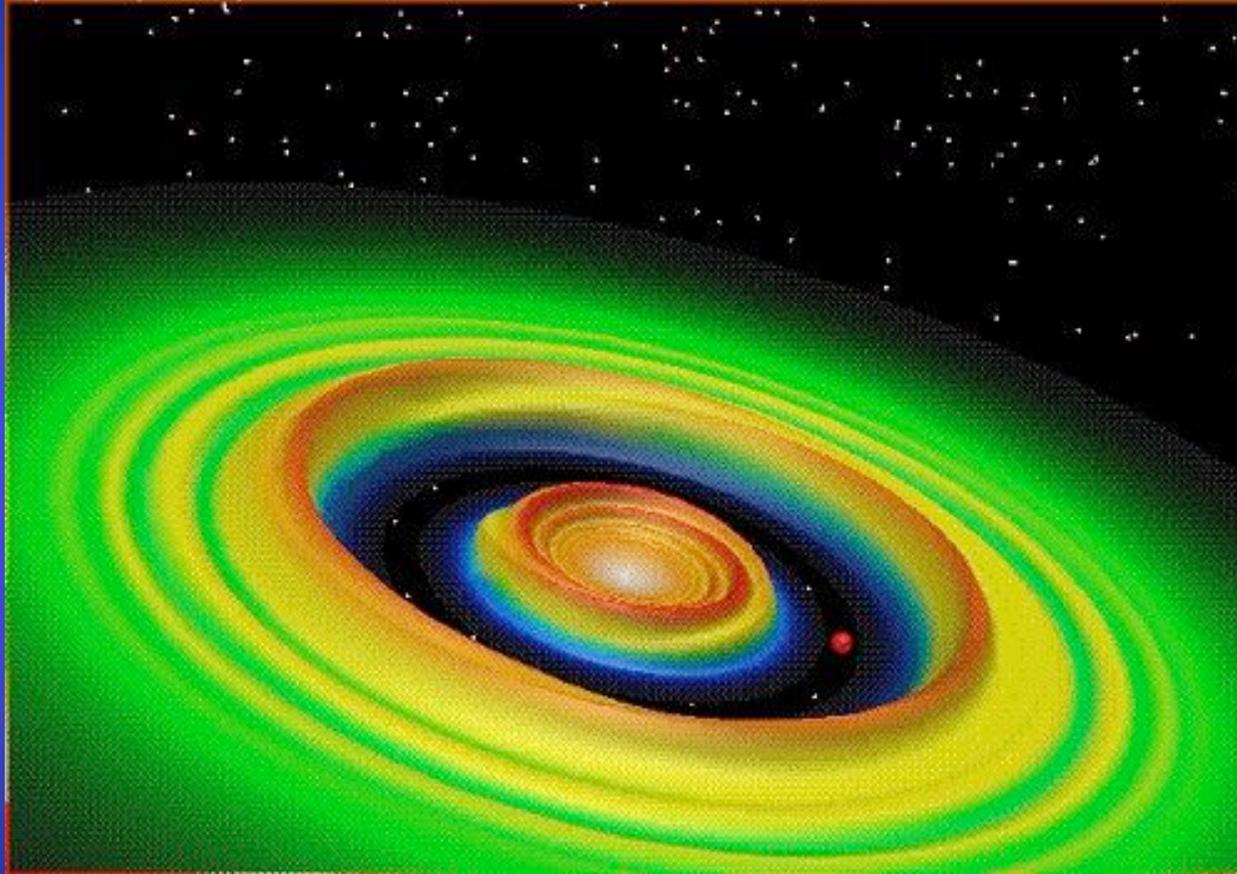
HD 69830 Zodiacal Disk Spectrum

Spitzer Space Telescope • IRS

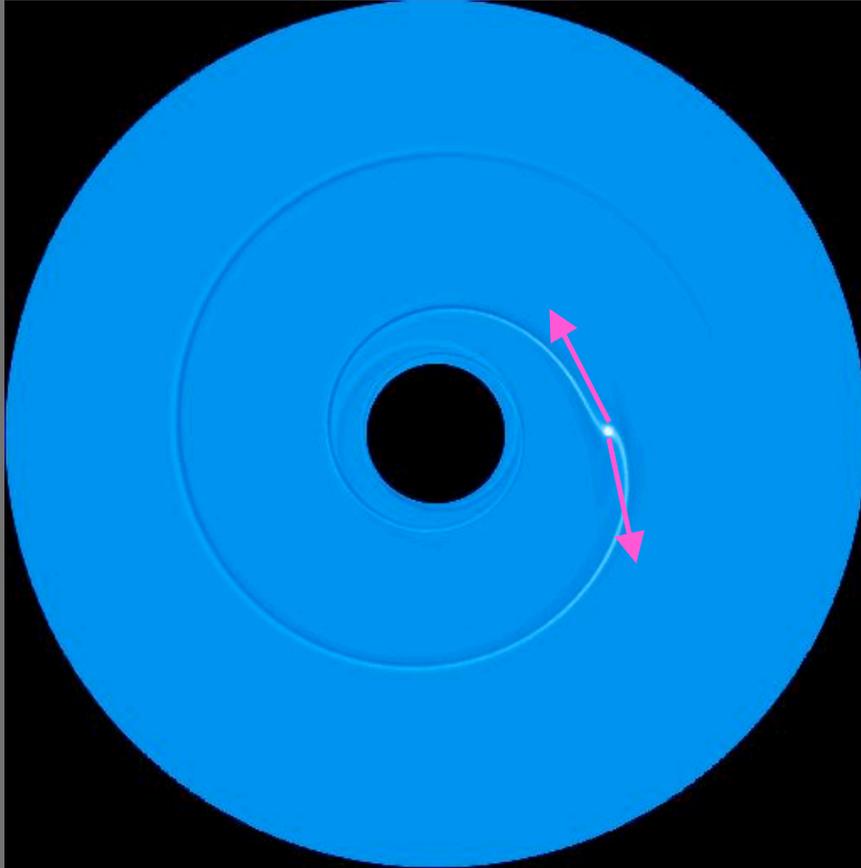
NASA / JPL-Caltech / C. Beichman (JPL)

Hale-Bopp spectrum: ISO
ssc2005-10a

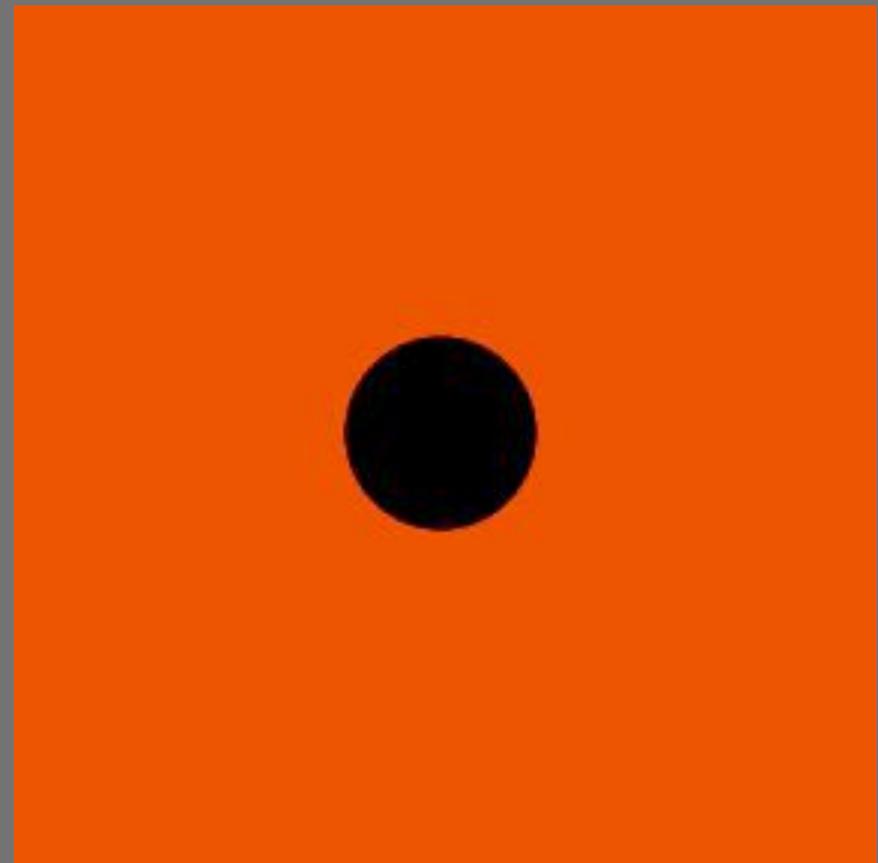
Forte interaction planètes-disque: sillages, sillons...



Migration planétaire : résumé première session



Couple du sillage : migration de type I. Rapide. Planètes de petite masse.

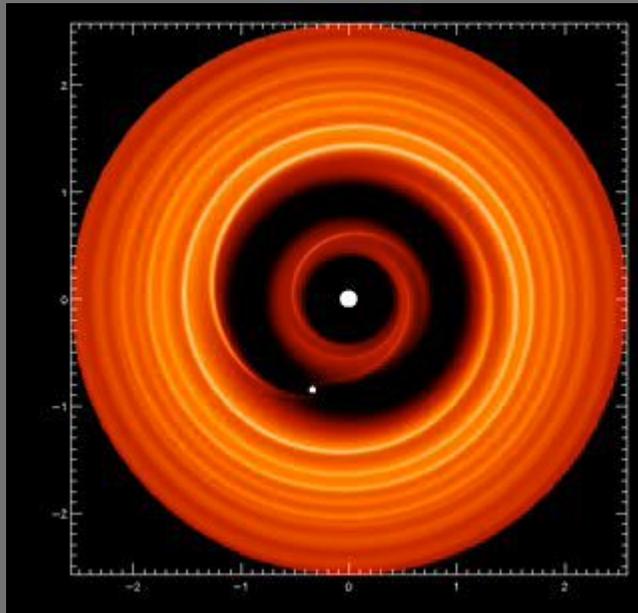


Migration de type II : avec sillon. Lente. Planètes géantes.

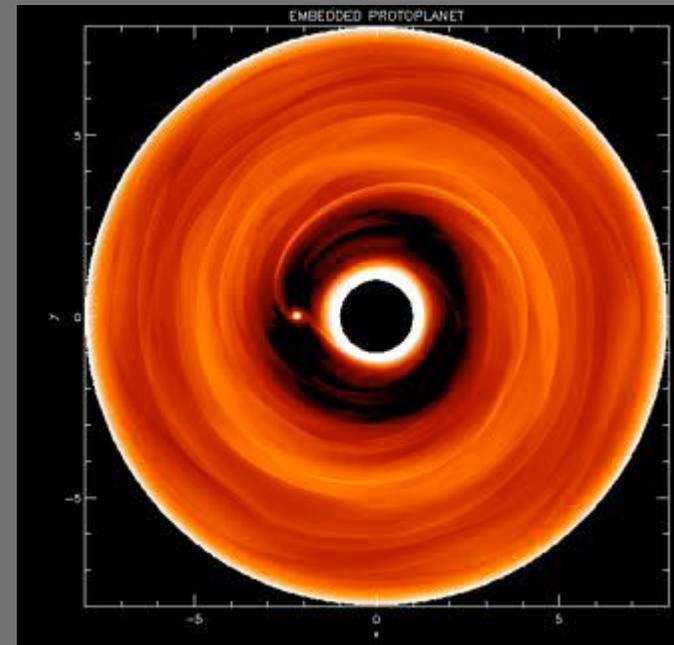
(F. Masset, Aussois 2004)

Ouverture des gaps en disques turbulents

Les mêmes auteurs se sont penchés sur le problème de l'ouverture des gaps par des planètes géantes dans des disques « *MR* » turbulents.

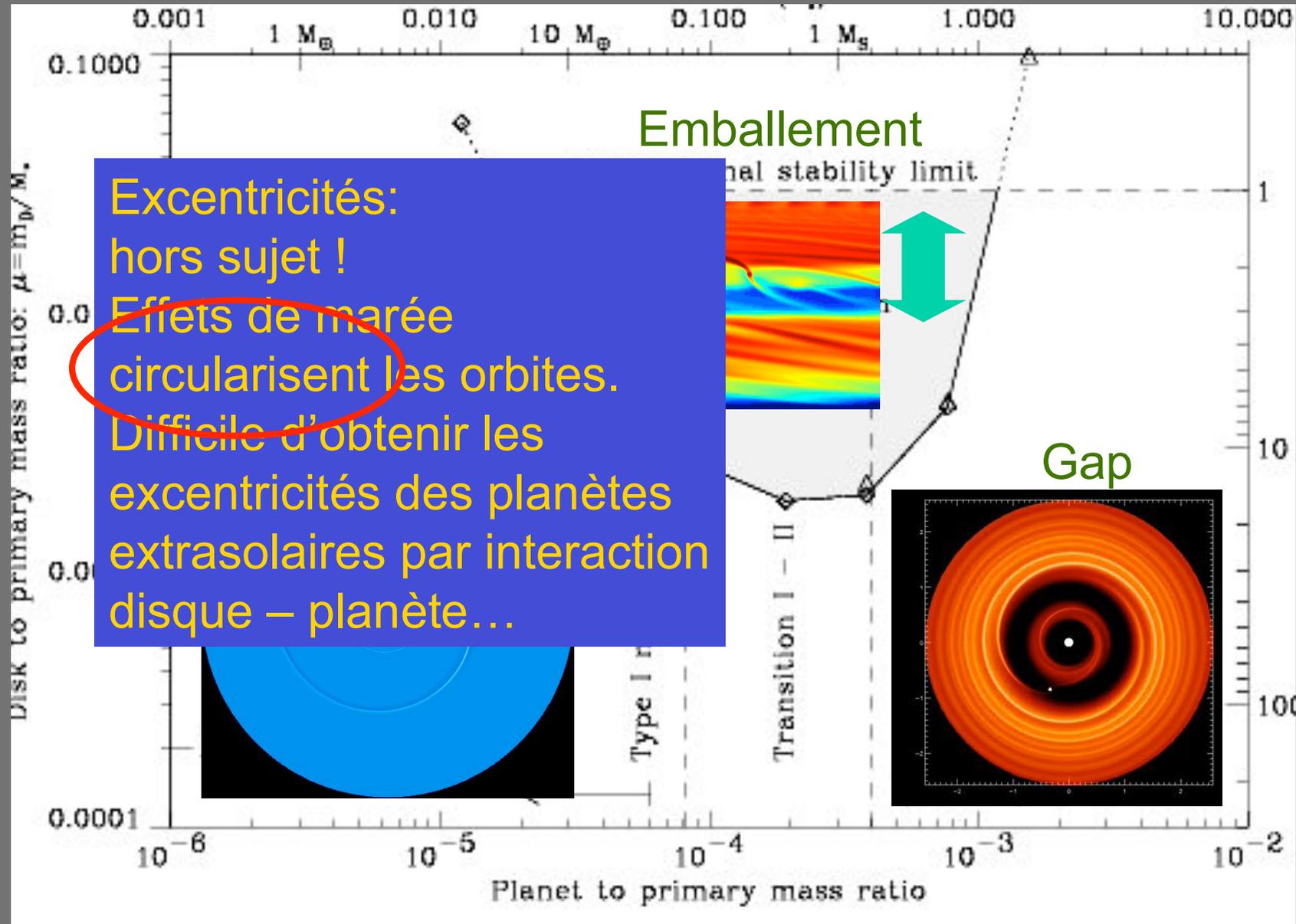


Planète géante en disque laminaire



Planète géante en disque turbulent

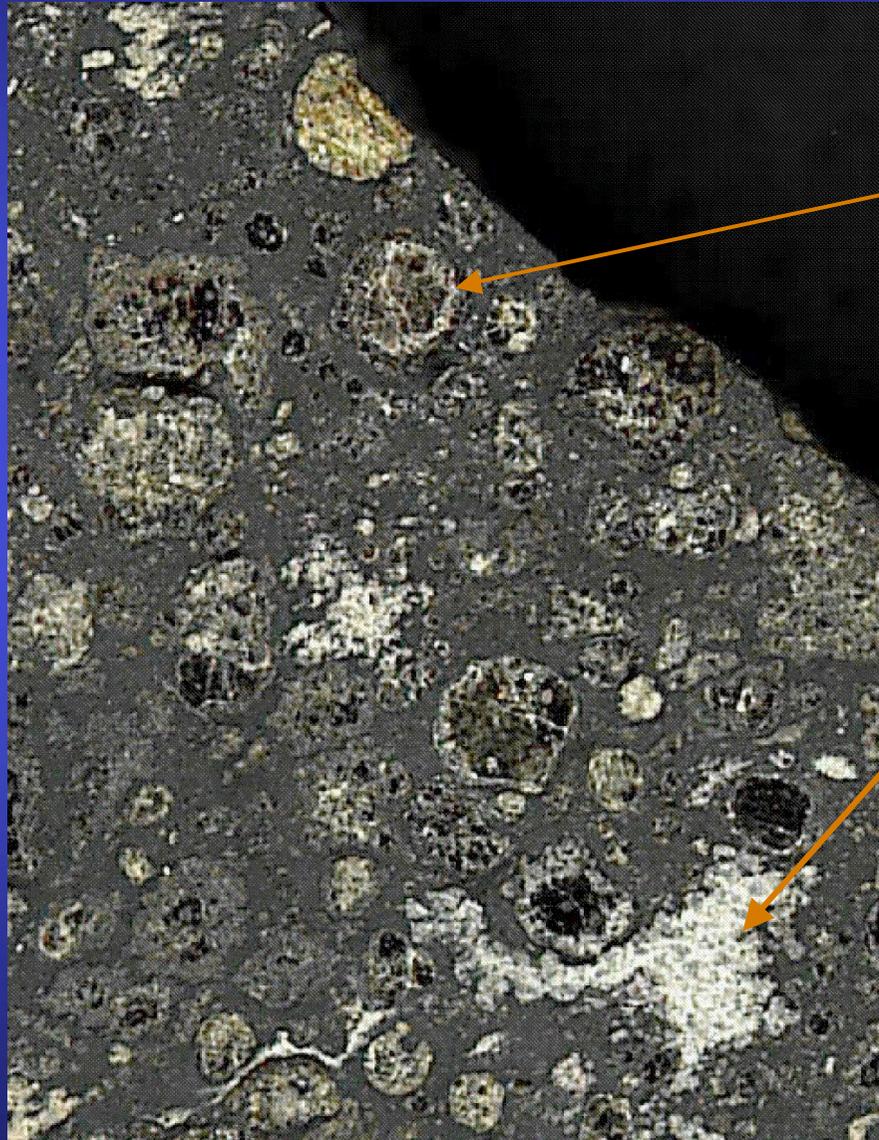
Résumé



Excentricités:
hors sujet !
Effets de marée
circularisent les orbites.
Difficile d'obtenir les
excentricités des planètes
extrasolaires par interaction
disque – planète...

2.3 Liens avec le système solaire jeune

Le problème des "radioactivités éteintes" dans les météorites



Chondres

« Inclusions (réfractaires)
Calcium-Aluminium » (CAIs):

= produits de désintégration
radioactive des isotopes

${}^7\text{Be}$ ${}^{10}\text{Be}$ ${}^{26}\text{Al}$ ${}^{36}\text{Cl}$ ${}^{41}\text{Ca}$ ${}^{53}\text{Mn}$ ${}^{60}\text{Fe}$
(“radioactivités éteintes”)

Gounelle, Chaussidon, Shu, et coll.

Météorite d'Allende (Mexique)

*Radioactivités éteintes (~ quelques millions d'années)
dans le système solaire jeune*

R/S	T (Ma)	Ab. CAIs	Abondance Gal.
$^{41}\text{Ca}/^{40}\text{Ca}$	0.1	1×10^{-8}	non
$^{26}\text{Al}/^{27}\text{Al}$	0.7	5×10^{-5}	non
$^{10}\text{Be}/^9\text{Be}$	1.5	9×10^{-4}	non
$^{60}\text{Fe}/^{56}\text{Fe}$	1.5	9×10^{-7}	non (*)
$^{53}\text{Mn}/^{55}\text{Mn}$	3.7	4×10^{-5}	non
$^{107}\text{Pd}/^{108}\text{Pd}$	6.5	$[4 \times 10^{-5}]$	oui
$^{182}\text{Hf}/^{180}\text{Hf}$	9.4	$[2 \times 10^{-4}]$	oui
$^{129}\text{I}/^{127}\text{I}$	16.7	$[1 \times 10^{-4}]$	oui

Recent discovery: ^7Be **T = 53 days,** Ab. $\sim 9 \times 10^{-7}$

Chaussidon et al. 2004

() Mostefaoui et al. 2005*

⇒ *Sur la piste de l'irradiation de la
"nébuleuse solaire primitive"*

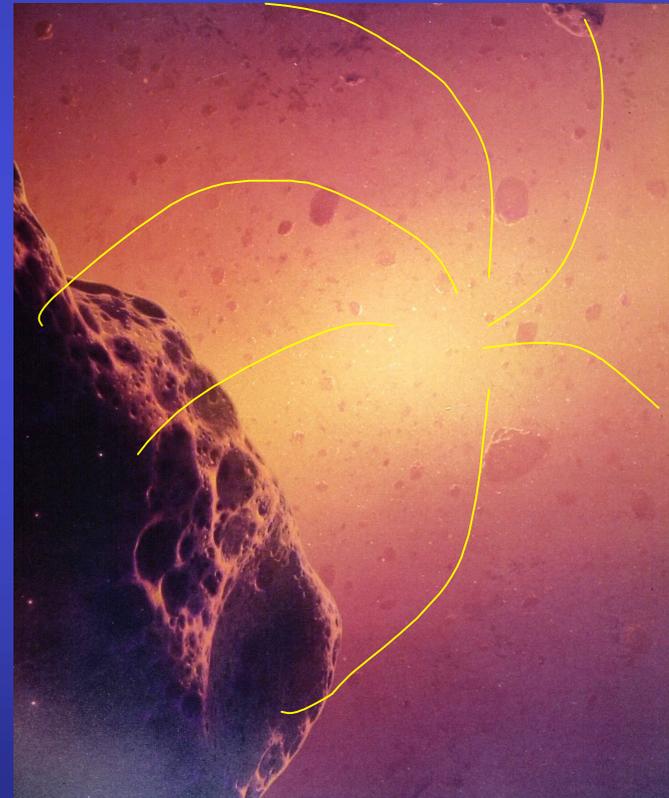
• *éruptions X : analogie avec le Soleil*

⇒ irradiation par particules de basse
énergie ($p, {}^3\text{He}, {}^4\text{He}$)

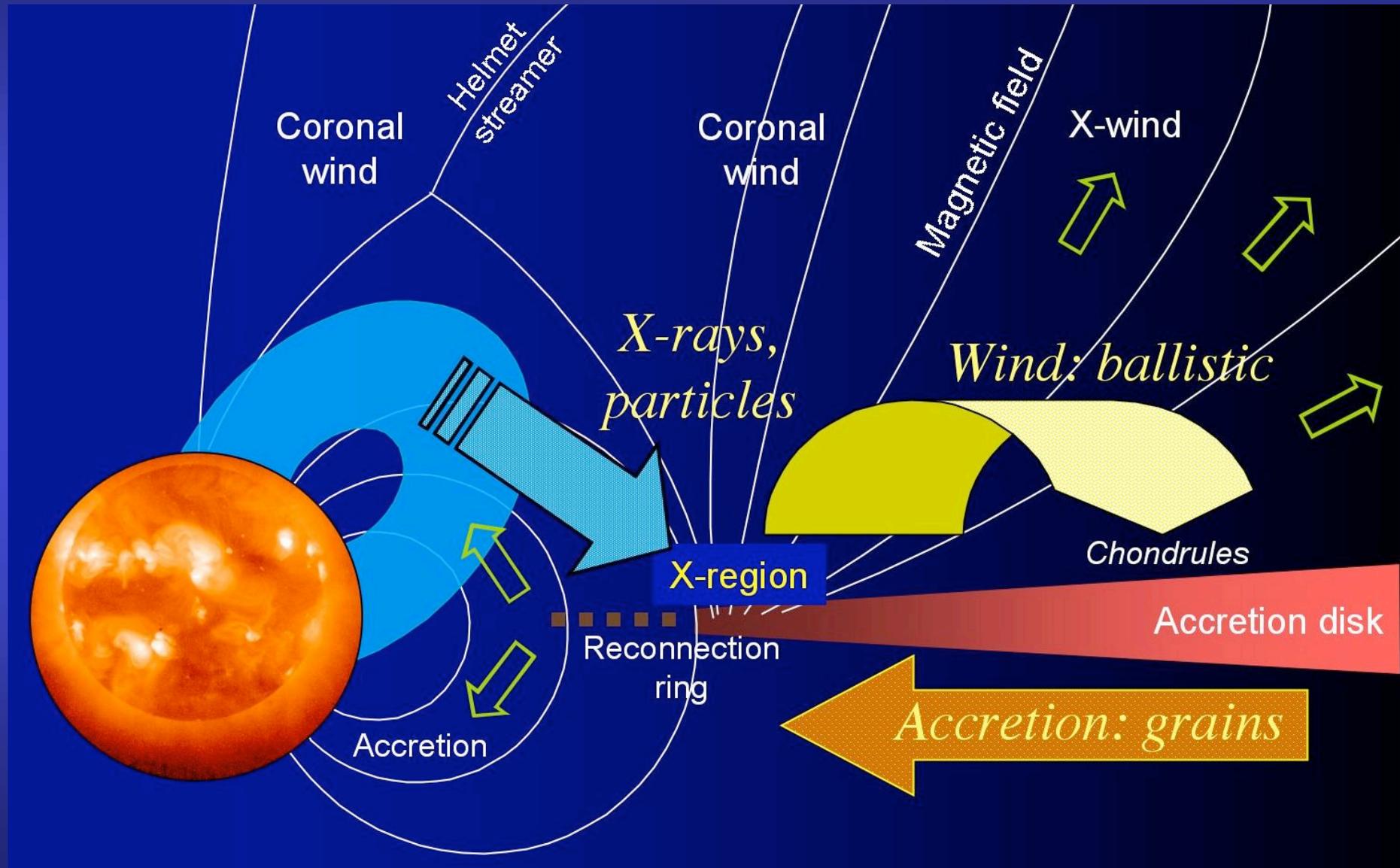
⇒ *Réactions nucléaires "en vol"*

résoud le problème de toutes les radioactivités
éteintes SAUF ${}^{60}\text{Fe}$: *Supernova ???*

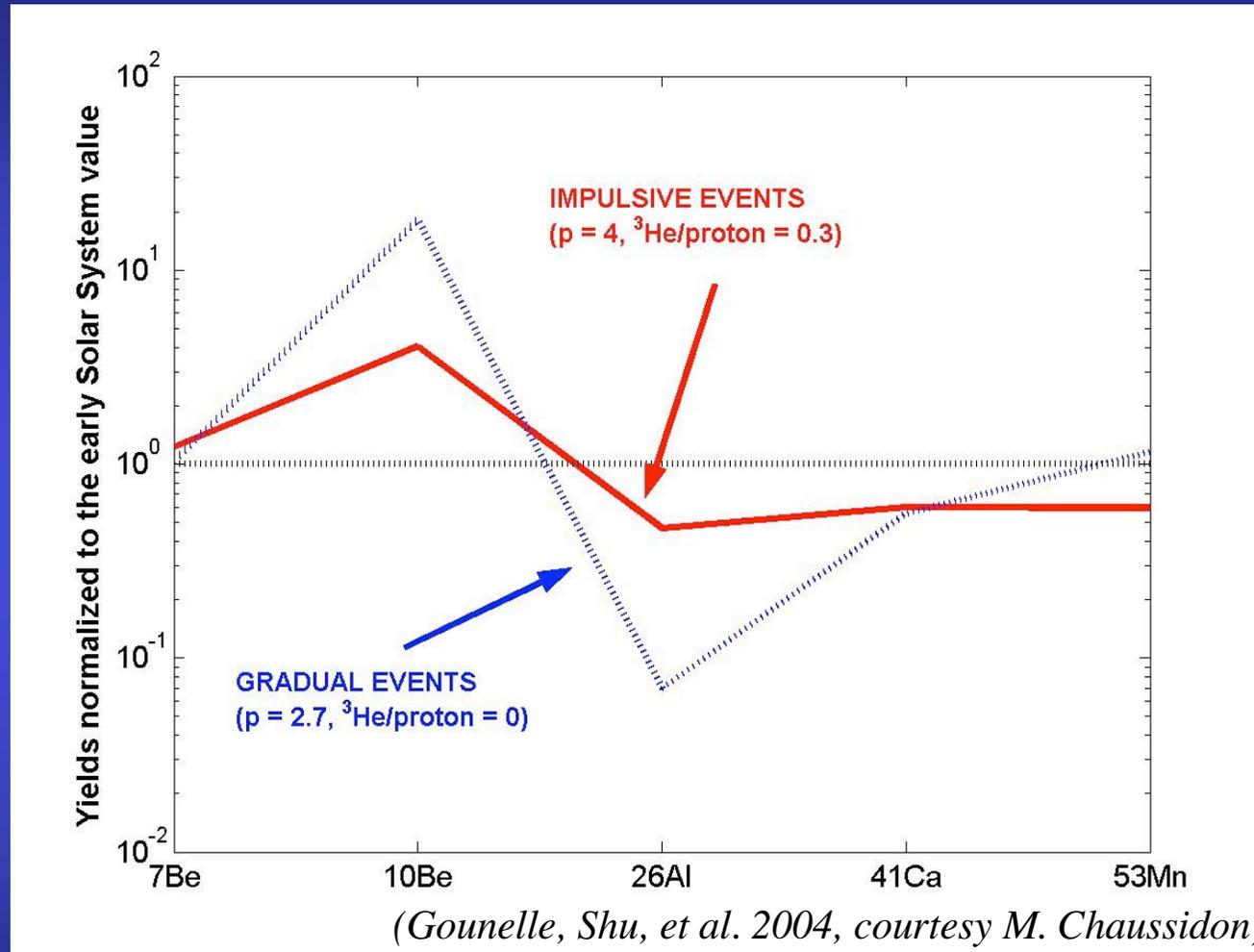
**OK pour le Soleil jeune, si
activité magnétique (rayons
X) augmentée de $\sim 10^3 - 10^4$:
*c'est ce qu'on observe dans
les étoiles d'Orion !***



*An attractive (but controversial) comprehensive model:
the “X-wind” model of Shu et coll.*

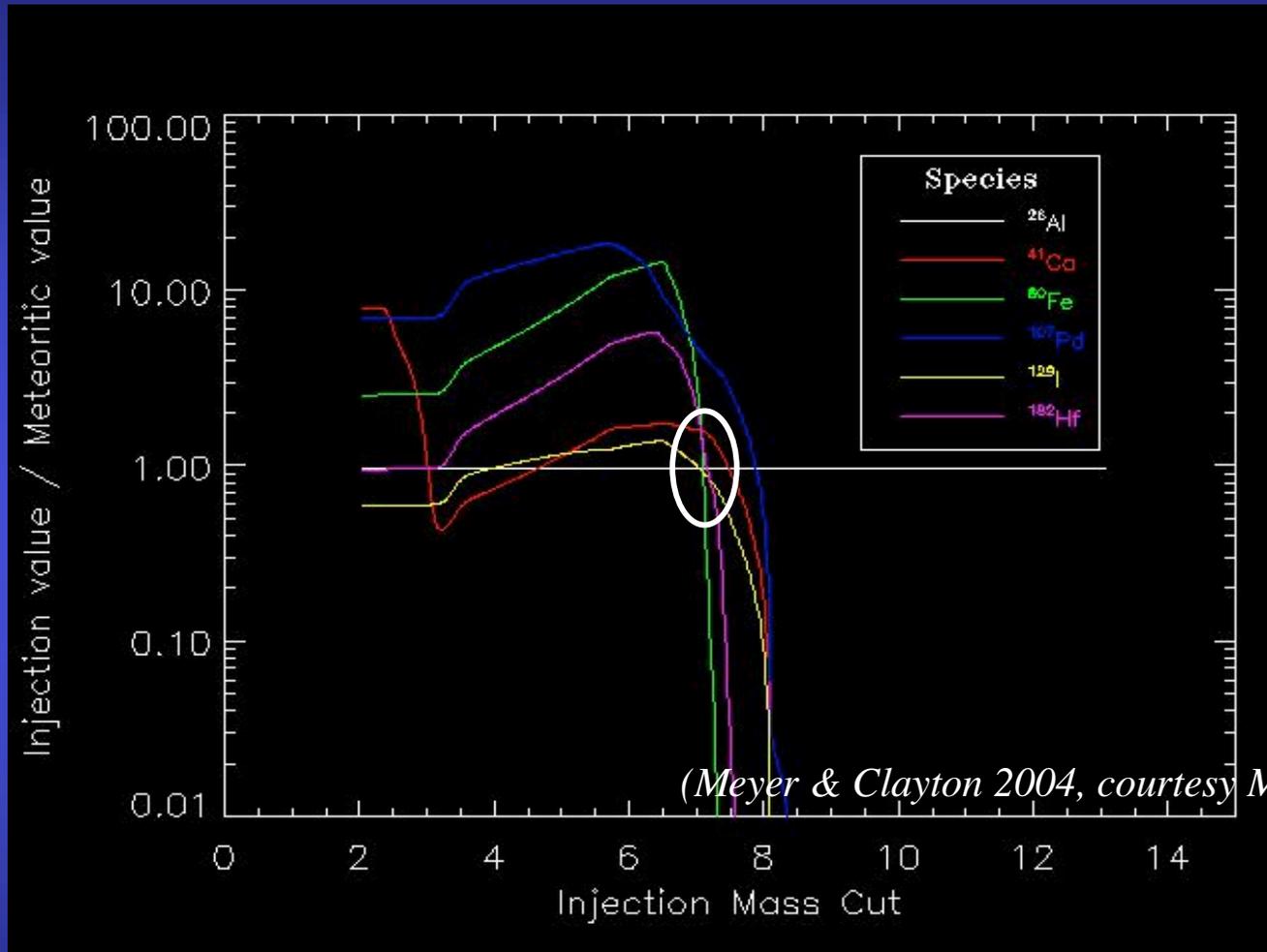


Irradiation model, scaled to X-ray flares



⇒ Can explain all nuclides, except ${}^{60}\text{Fe}$; *generic*
(i.e., works for all solar-like stars and all star-forming regions)

Nearby SNIi injection model



⇒ Can explain all nuclides, except ^7Be and ^{10}Be ; *not generic*
(i.e., works only for a special SN, at a special distance, in massive star-forming regions)

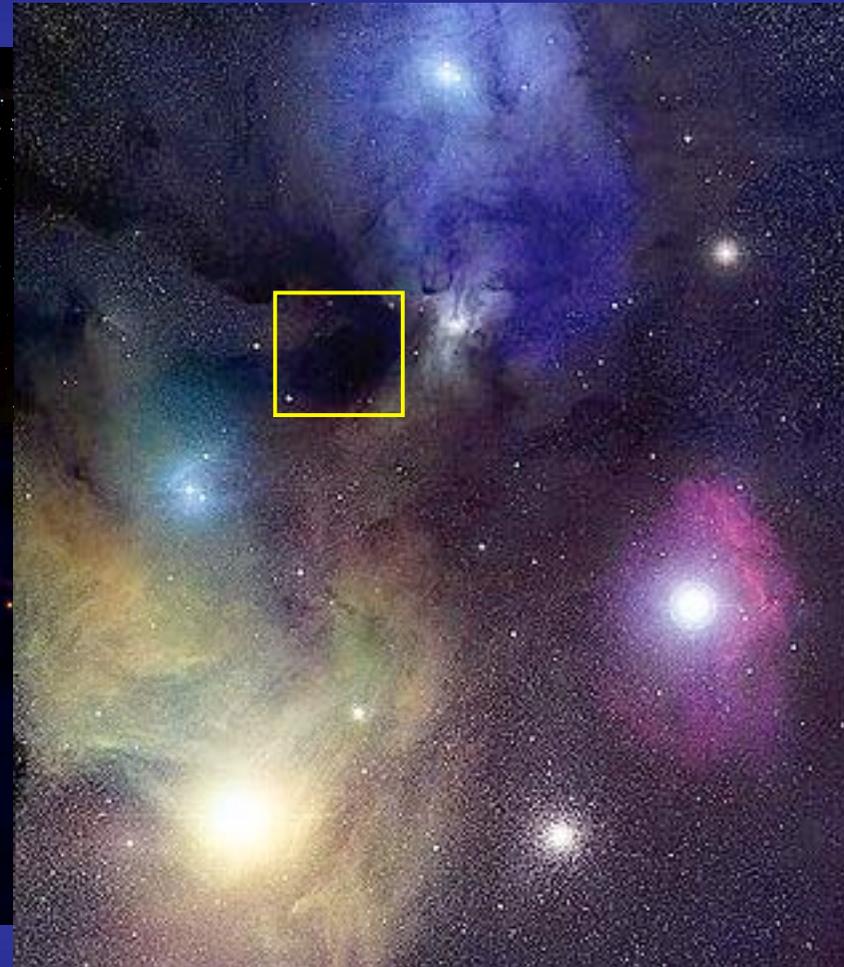
A suivre: exposé de Marc Chaussidon

2.4 Où le Soleil est-il né ?

Dans quel genre de berceau le Soleil est-il né ?

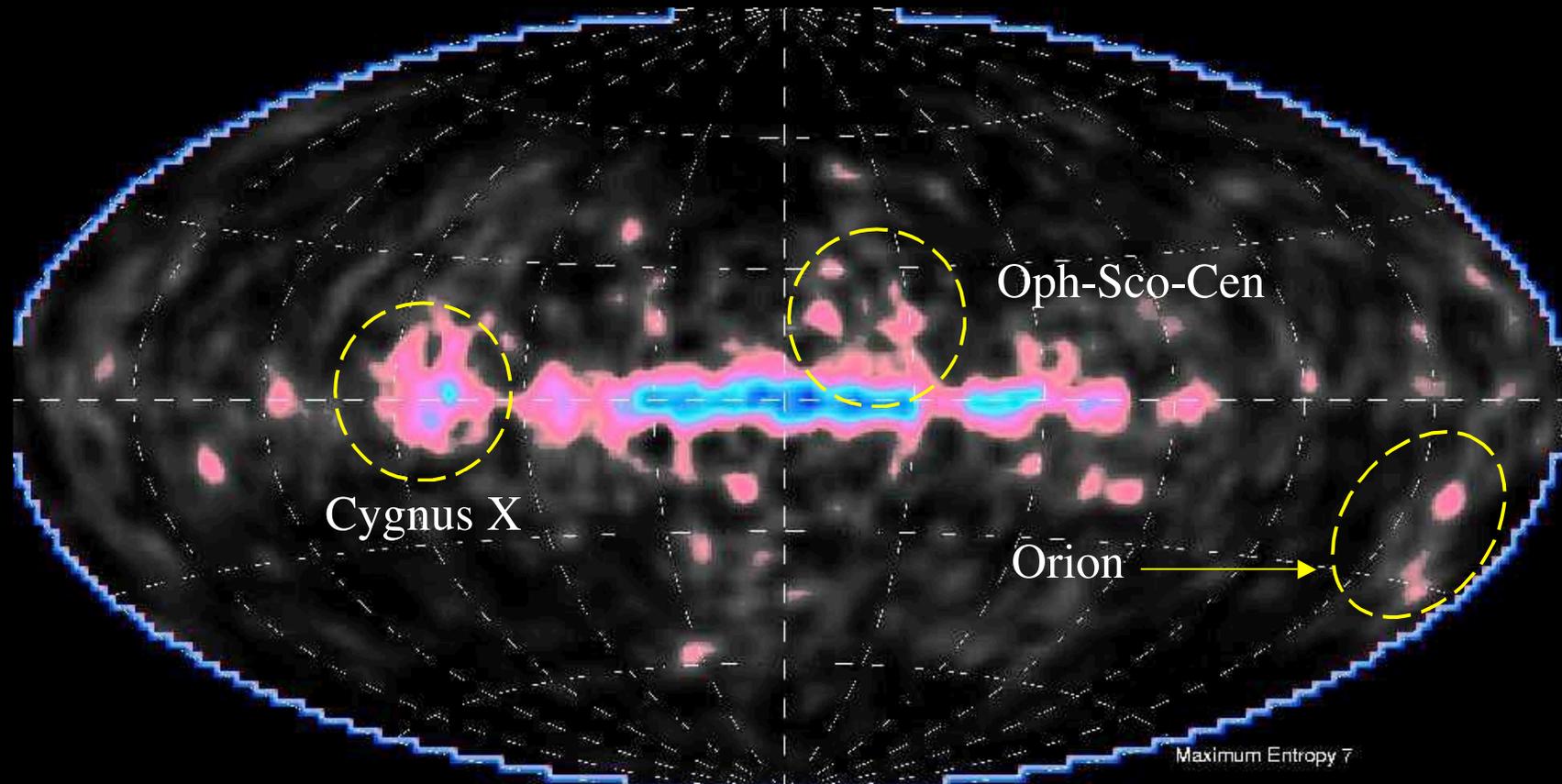


Association riche type Orion: $P \sim 90\%$
(Adams & Myers 2001, Lada & Lada 2003)



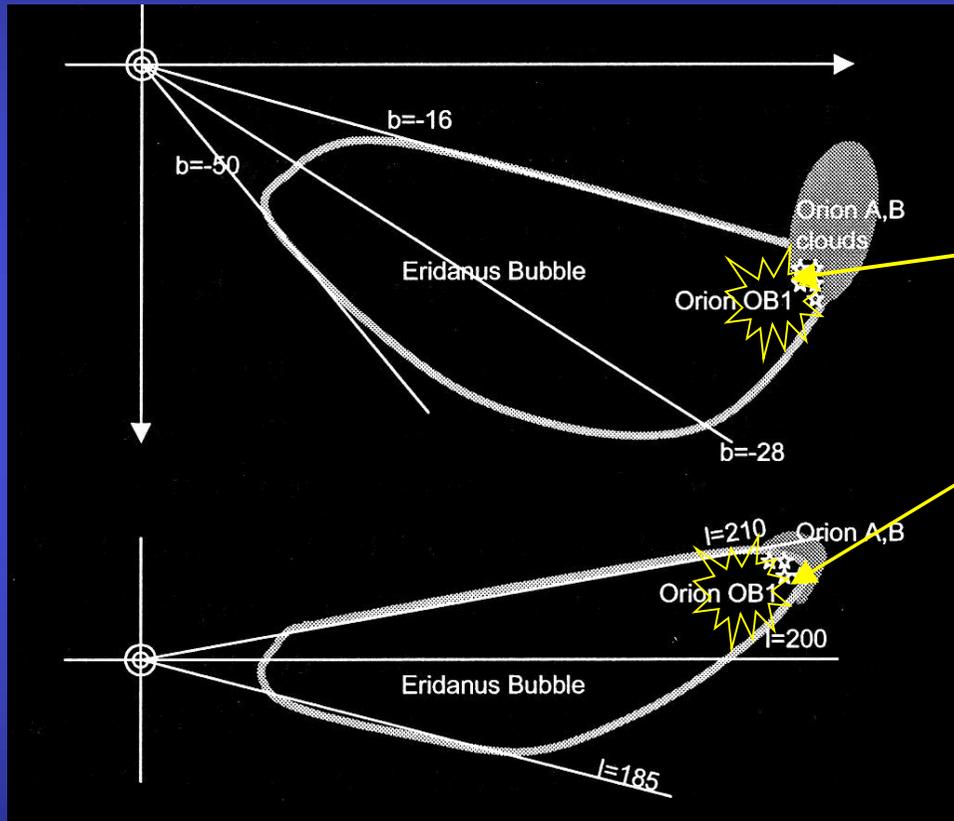
Amas pauvre type ρ Oph: $P \sim 10\%$

The Milky Way @ 1.809 MeV : live ^{26}Al

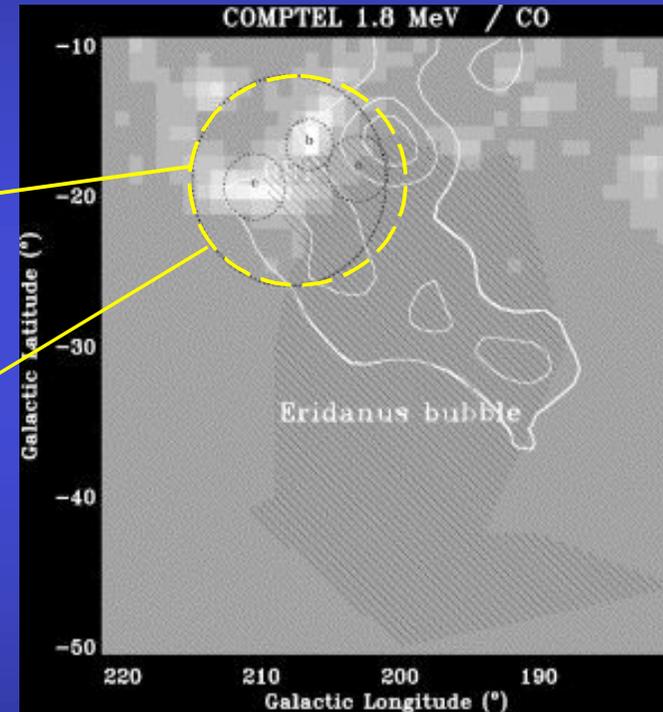


GRO Comptel (2001)

The “one-million-year” Orion ^{26}Al emission:
at the edge of the molecular cloud



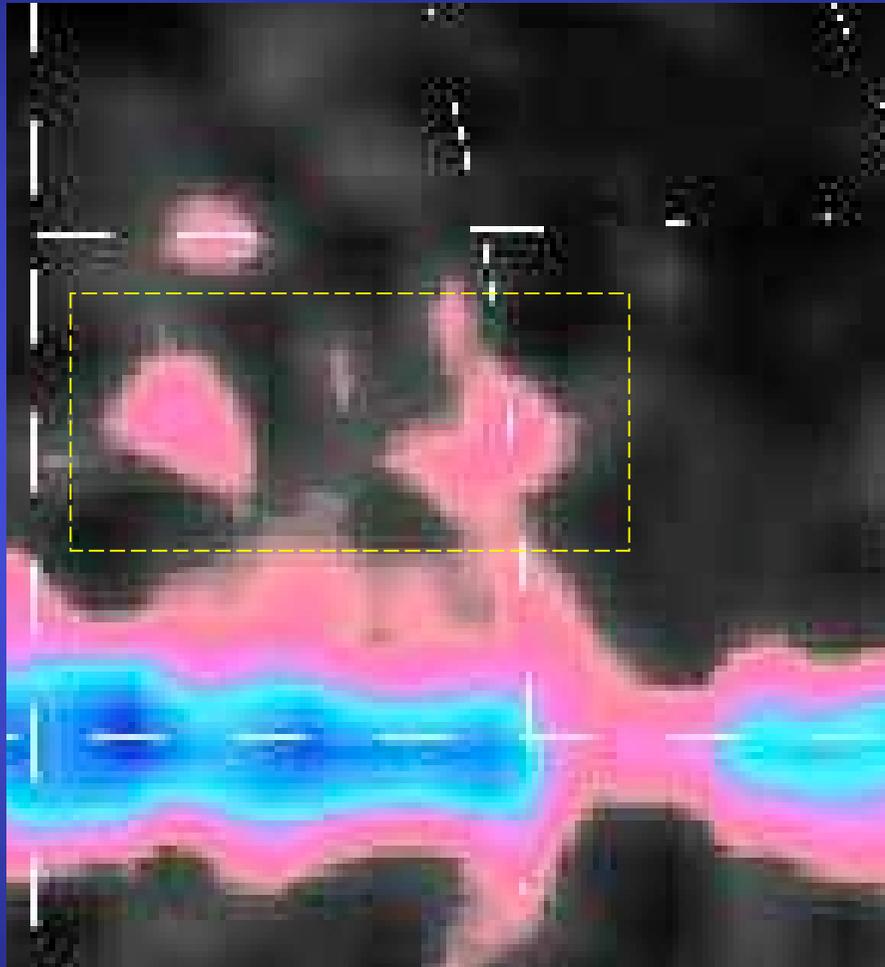
The Eridanus Superbubble



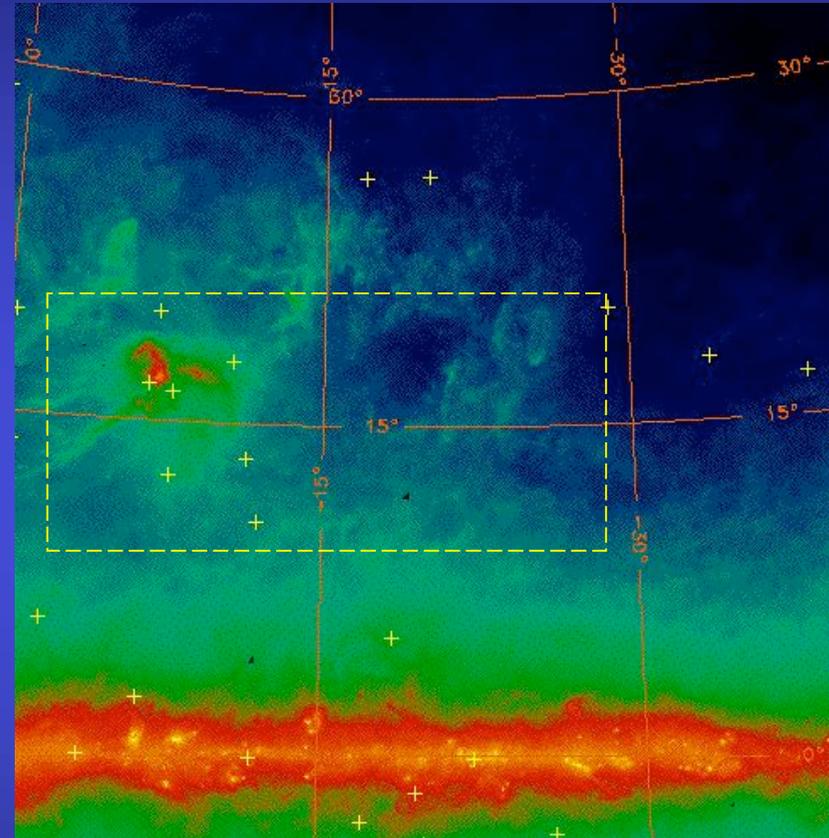
1.809 MeV (Diehl et al. 2004)

$$\Phi_{\gamma} \sim 10^{-4} \text{ cm}^{-2} \text{ s}^{-1}$$

The Oph-Sco-Cen ^{26}Al emission



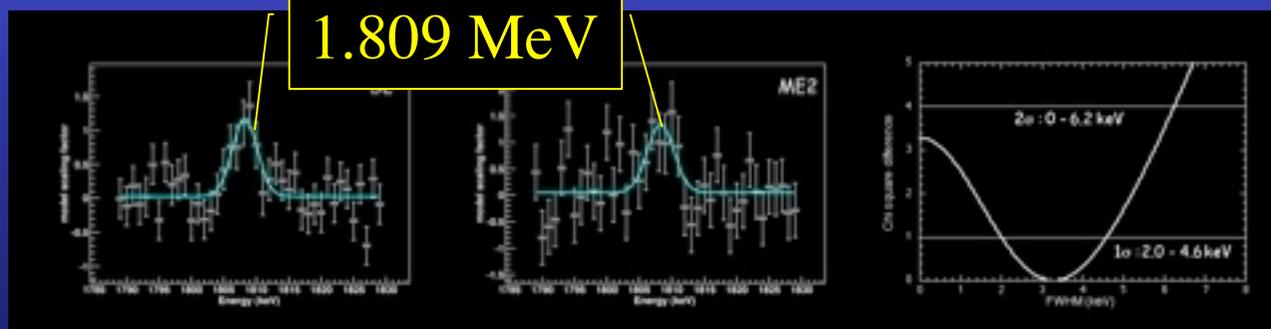
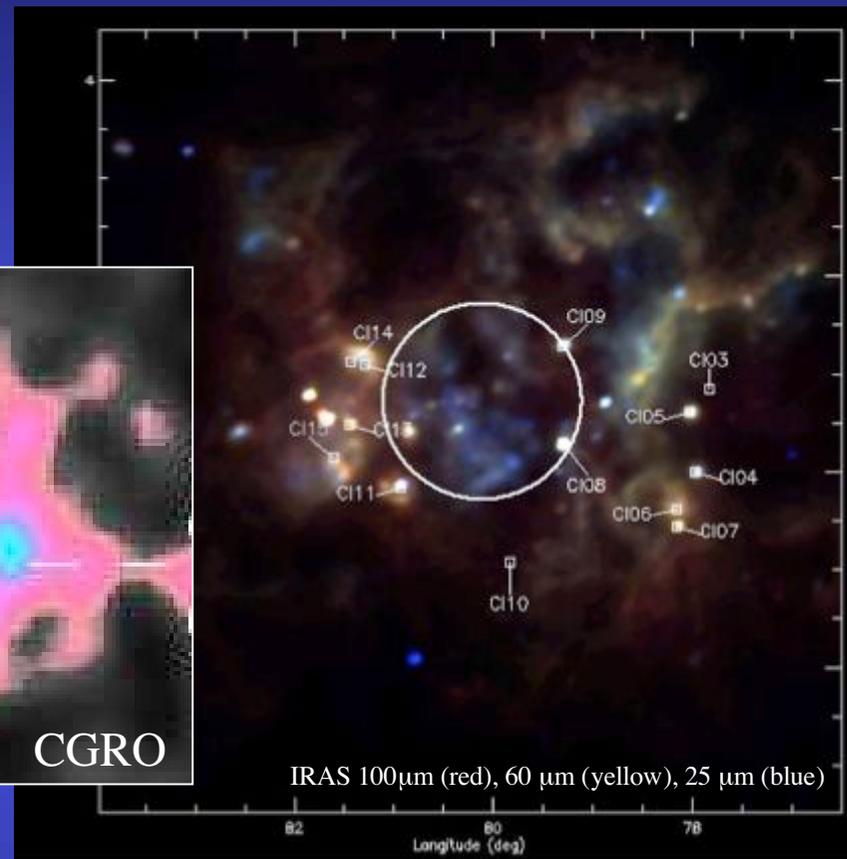
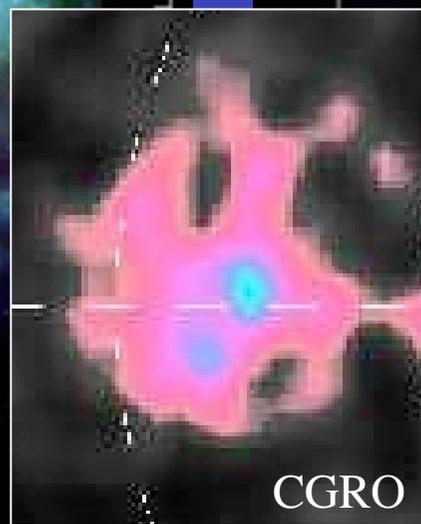
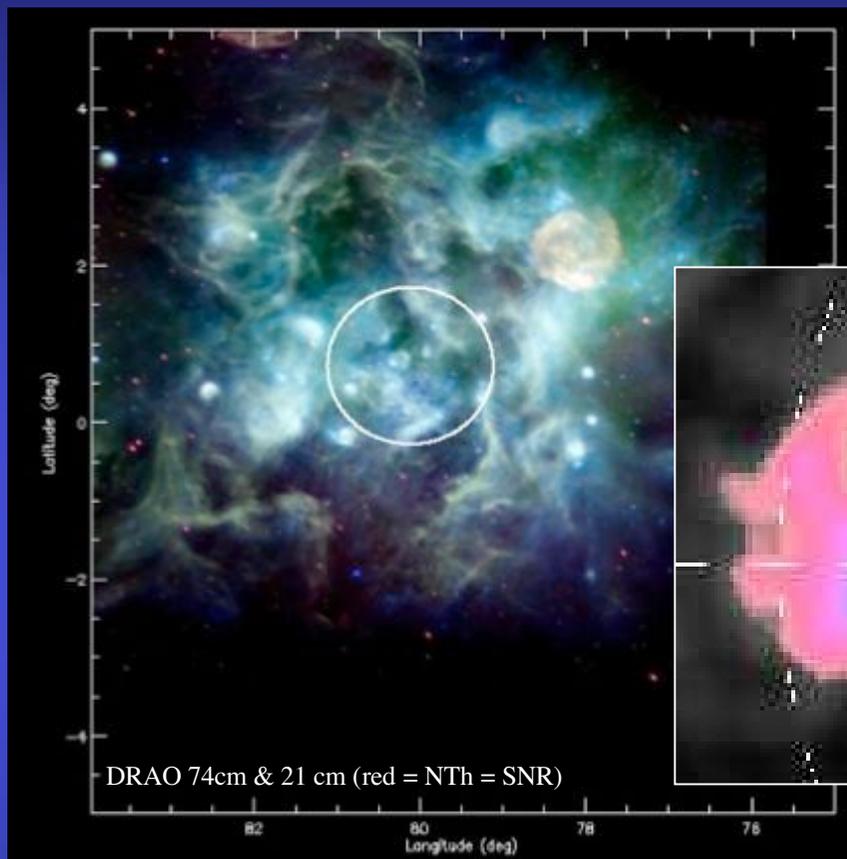
1.809 MeV $\Phi_\gamma \sim \text{few } 10^{-5} \text{ cm}^{-2} \text{ s}^{-1}$



IRAS 100 μm

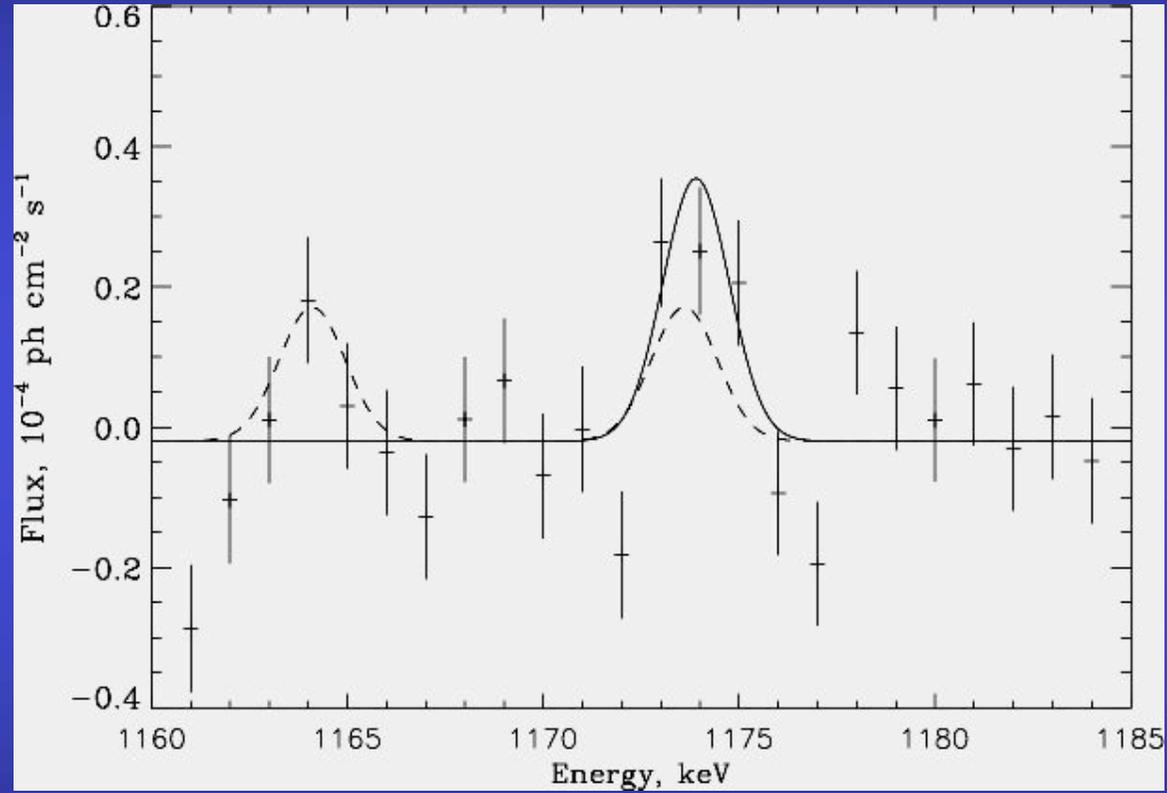
(Montmerle 2002)

The Cygnus X ^{26}Al emission



INTEGRAL
(Knödlseder et al. 2004)

RHESSI ^{60}Fe detection confirmed by INTEGRAL



$$\Phi_{\gamma} = 3.7 \pm 1.1 \times 10^{-5} \text{ cm}^{-2} \text{ s}^{-1}$$

INTEGRAL
(Harris et al. 2005)

INTEGRAL γ -rays from SFRs...

- Interstellar ^{26}Al consistent (~ 2) with theoretical predictions for massive star yields
- Very recent result: **interstellar ^{60}Fe detected** (RHESSI result, 2004, confirmed). Neutron-rich, unambiguous signature of *explosive nucleosynthesis* in « **core-collapse SN** » (observed as "SNII": $M_* > 8 M_\odot$).
- Observed $^{60}\text{Fe}/^{26}\text{Al}$ line ratio = 0.11 ± 0.03 , predicted ~ 0.2
 - \Rightarrow **Extra source of ^{26}Al** : pre-explosion ejection (late stages with massive winds, WR phase) ?
 - More statistics needed (Harris et al. 2005, Knödelseder 2005)
 - Nearby SFRs undetectable in ^{60}Fe - flux too low ($\sim 10\%$ ^{26}Al)

Où le Soleil est-il né ?

à retenir... (1)

- La détection de rayons X dans toutes les étoiles jeunes de "petite" masse rend incontournable l'**irradiation des disques**, prouvée *directement* par la raie de fluorescence X à 6,4 keV, et dans le système solaire jeune par le ${}^7\text{Be}$ ($t_{1/2} = 53 \text{ j}$)
- La détection de ${}^{60}\text{Fe}$ rend incontournable **la présence d'une SNII** ($M_* > 8 M_{\odot}$) au voisinage du Soleil en formation ($< 10^6 \text{ ans}$)
- L' ${}^{26}\text{Al}$ (et les autres nuclides à vie courte) peut s'expliquer dans les deux modèles: étrange coïncidence ? (SN "spéciale" ...)

Où le Soleil est-il né ?

à retenir... (2)

- Les observations γ montrent l'existence de *nucléosynthèse "en direct"* d' ^{26}Al et de ^{60}Fe interstellaire dans les régions de formation d'étoiles massives (associations OB)
- "Surproduction" (fact. ~ 2) observée de ^{26}Al par rapport à ^{60}Fe si SNII seulement: *pb* ?
- Favorise une naissance du Soleil dans une association de type \geq Orion, mais pose d'autres problèmes (*survie des disques*: vents, UV, X...)
- Des associations OB avec SN existent dans la galaxie, mais sont *rare*s (sources γ , ~ 30 "SNOBs": Montmerle 1979 !)

ON GAMMA-RAY SOURCES, SUPERNOVA REMNANTS, OB ASSOCIATIONS,
AND THE ORIGIN OF COSMIC RAYS

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ABSTRACT

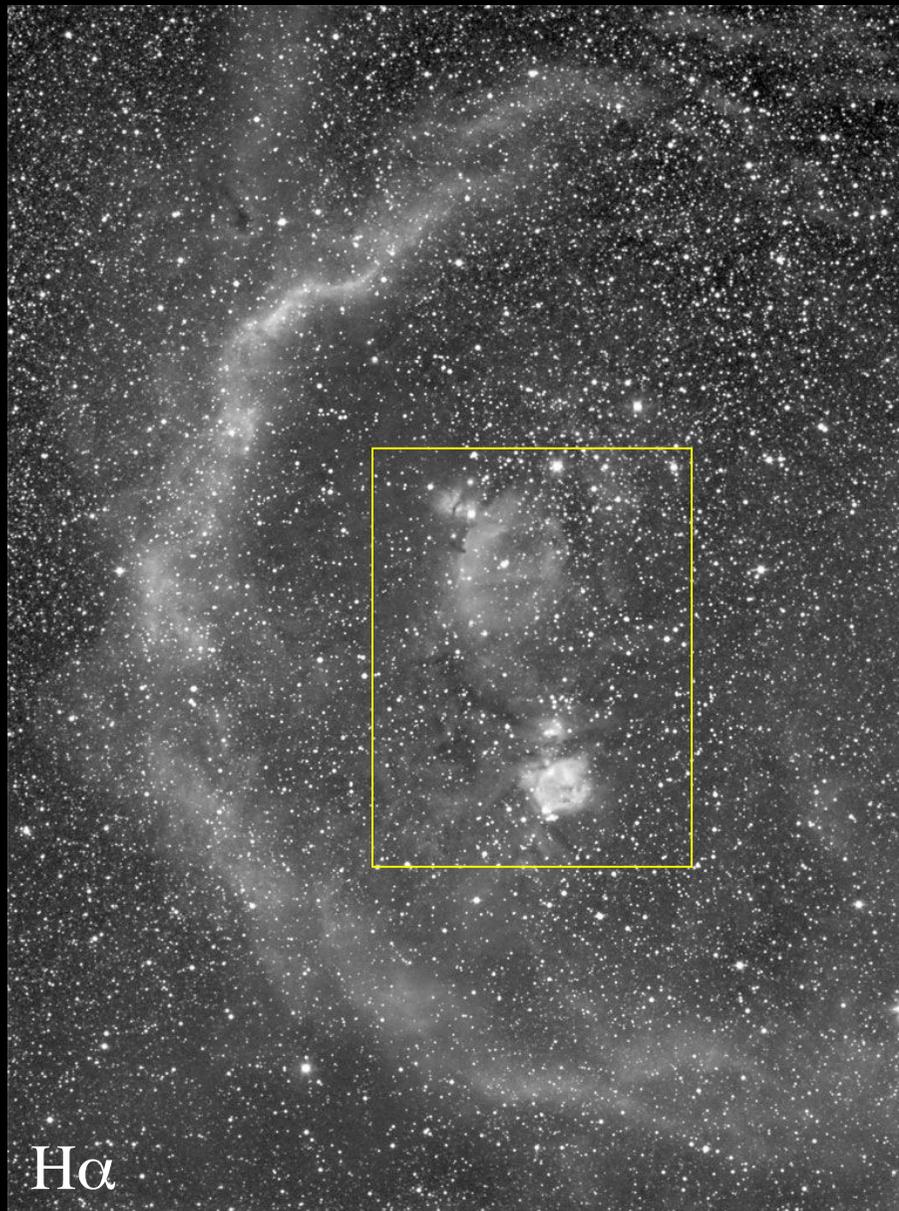
Although supernova explosions are widely thought to give rise to cosmic rays (nucleons), there is, as yet, no direct evidence from individual objects to support this view. A possible tool in this respect is the detection of γ -rays emitted by supernova remnants (SNRs) via π^0 decay, which results from high-energy cosmic ray interactions with the ambient matter. However, the accumulating γ -ray data (in particular from the *Cos B* satellite) show that SNRs as a class are not γ -ray sources, but rather that γ -ray sources are, in general, closely linked with young objects. Bearing in mind the cosmic-ray production problem, we examine, among other possibilities, if a *restricted* class of SNRs are actually γ -ray sources; we restrict the class to those SNRs physically linked with extreme Population I objects.

Along these lines, spatial coincidences between SNRs and OB associations or H II regions (SNOBs) are sought by various methods, and this yields a list of about 30 objects (which is certainly incomplete). From the *Cos B* data, one finds that five (perhaps six) out of 11 as yet unidentified γ -ray sources (above 100 MeV) are associated with SNOBs, and there is a hint that as much as three-fourths of the best identified SNOBs are seen in γ -rays. The associated probabilities of chance coincidence are $\sim 10^{-4}$. Angular and other statistical considerations also support this association.

Pending confirmation, if a substantial proportion of the observed γ -rays does come from π^0 decay, SNOBs appear to be a major source of galactic cosmic rays, in which cosmic-ray (≥ 2 GeV) energy densities in the range ~ 10 –100 times the solar neighborhood value are found. To lead the way toward a possible model for the origin of cosmic rays consistent with the γ -ray data, a phenomenological scenario is suggested. In this scenario, cosmic rays are produced by a two-step process, in which low-energy (MeV range) particles are injected by young stars pertaining to an OB association, and are subsequently accelerated by the shock wave of a neighboring supernova explosion.

In this context, we discuss such items as the case of "isolated" SNRs, the possible links with light-element production, further observational tests, and the links between SNOBs and other astronomical objects.

Subject headings: clusters: associations — cosmic rays: general — gamma-rays: general —
nebulae: supernova remnants — stars: flare



H α

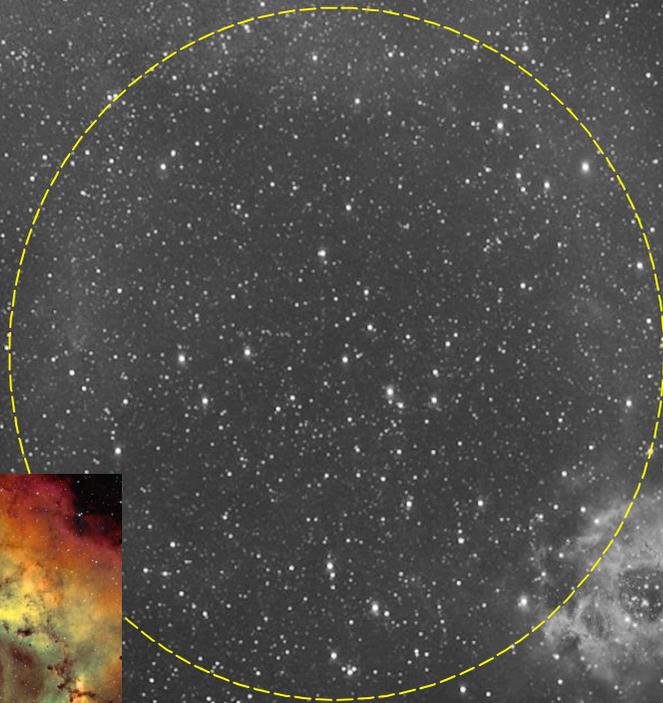
Orion and Barnard's loop:
= 20 SN, $\sim 10^6$ yrs ago...



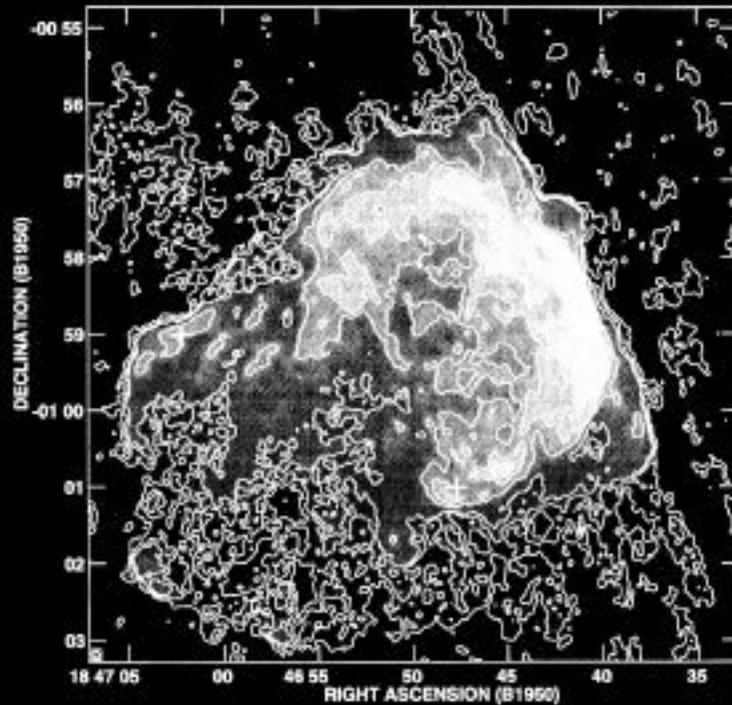
Cone-NGC2264



Monoceros Loop



Rosette-NGC2244

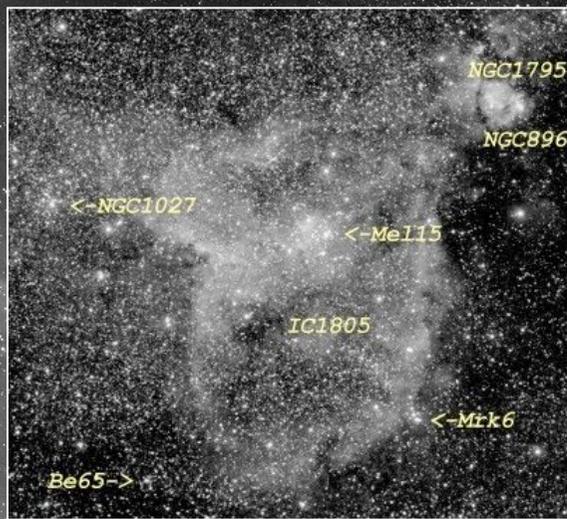
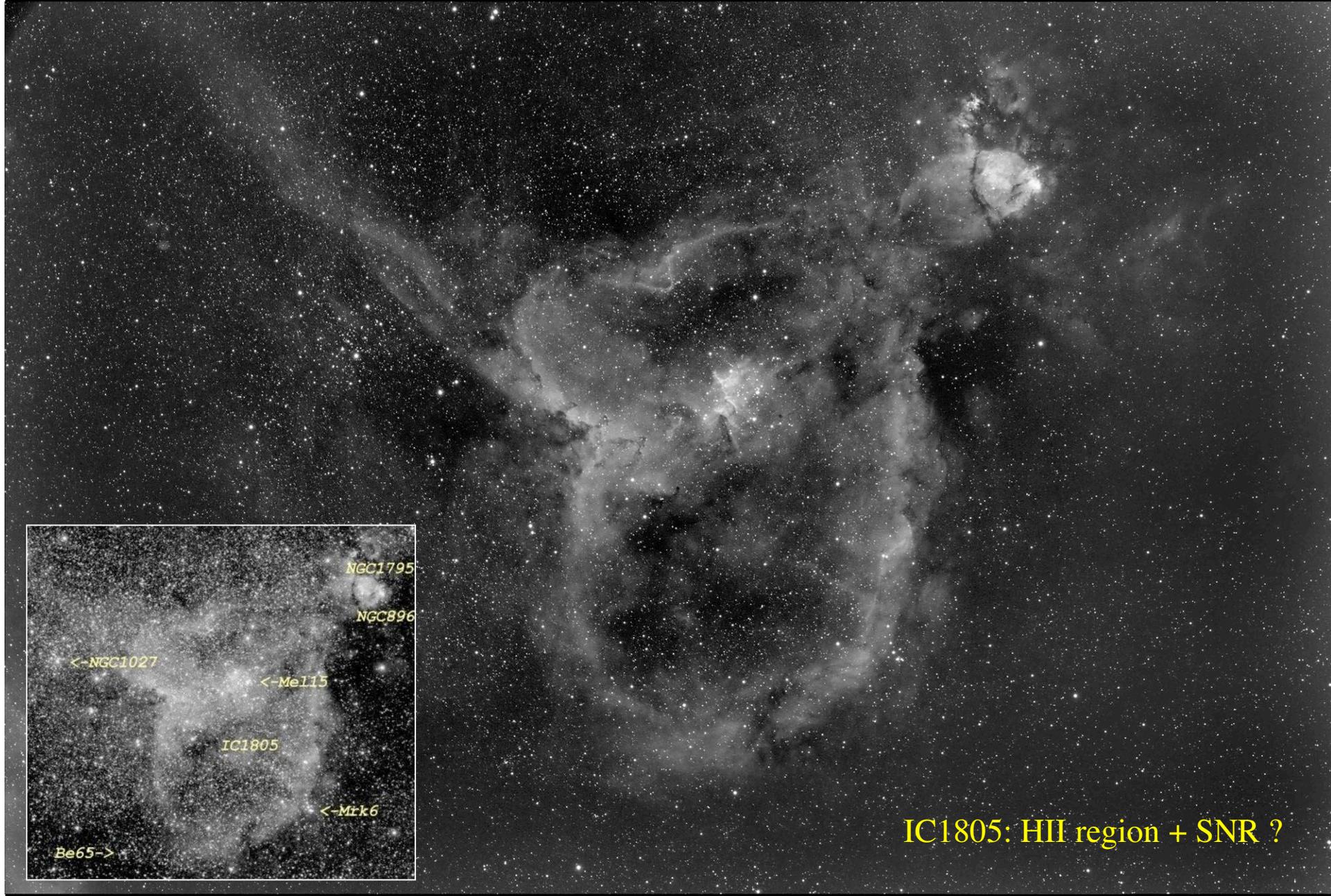


3C391 SNR (VLA)

*Pile-up against molecular clouds:
How is SN material mixed with cloud
material ??*



IC443 SNR (optical)



IC1805: HII region + SNR ?

Questions ouvertes... (Aussois III ?)

- Évaporation des disques: fréquente ou rare ?
- L'agglomération des grains (et donc la formation des planétésimaux) est-elle *favorisée* par les UV ?
- Cela résoud-il le passage cm \rightarrow km ?
- Disques vs. système solaire: comment passer de 500 AU à 50 AU ?
- L'explosion d'une SN proche du Soleil naissant (rare) est-elle importante pour l'évolution du système solaire ?
- Comment s'opère le transport de la matière d'une SN à l'intérieur d'une région de formation d'étoiles ?

