Le "bing bang" de la formation du Soleil

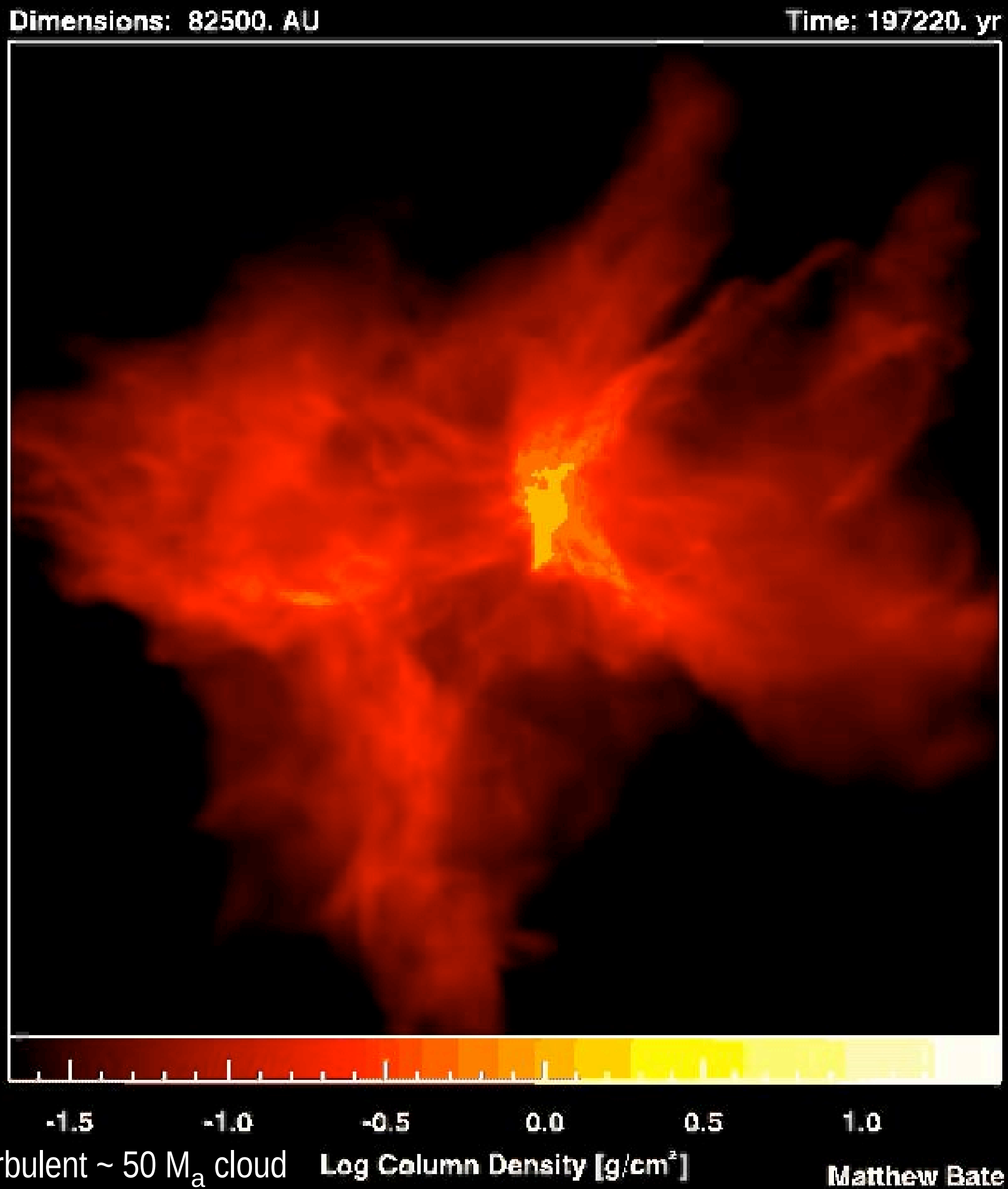
Thierry Montmerle
Laboratoire d'Astrophysique de Grenoble, France

Plan…

- 1. Les premières étapes de l'évolution des étoiles de type solaire
- 2. Observer les régions de formation d'étoiles à haute énergie: les rayons X et le magnétisme stellaire
- 3. Les archives météoritiques et le berceau du Soleil
- 4. Conclusions: la formation du système solaire aujourd'hui

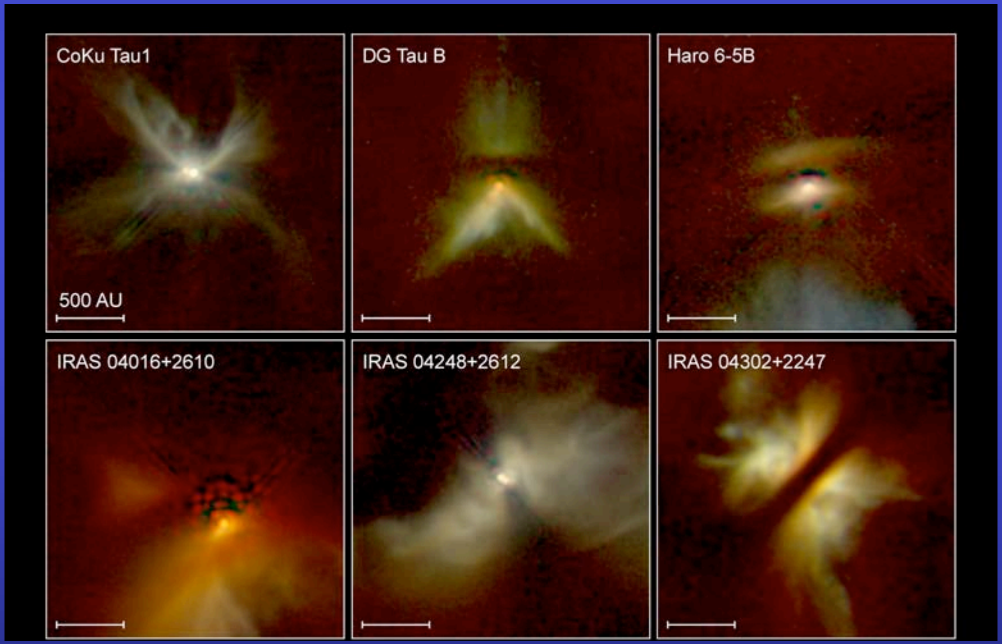
1. Les premières étapes de l'évolution des étoiles de type solaire

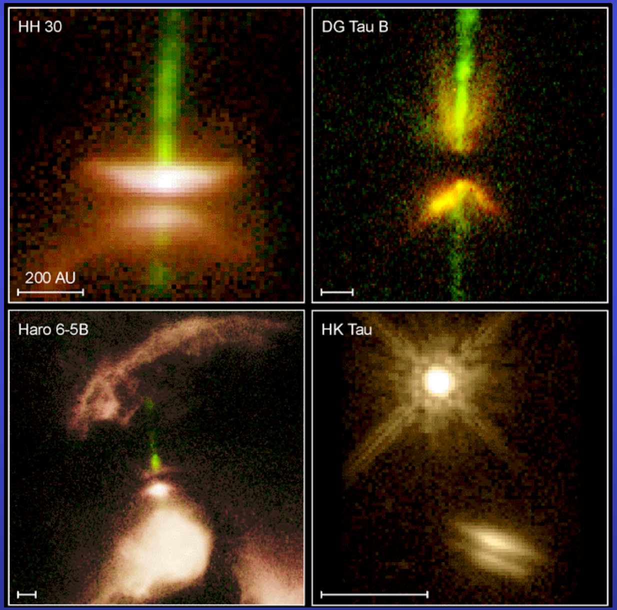
- Zoom: des "protoétoiles" aux étoiles "T Tauri"
  - La formation d'étoiles en amas
  - Protoétoiles: la phase "invisible", enfouie dans les nuages moléculaires
  - L'ubiquité des disques et des jets: le phénomène "d'accrétion-éjection"
- Les disques circumstellaires/protoplanétaires
  - Durée de vie
  - Evolution: vers la formation planétaire



Star formation in a turbulent ~ 50 M_a cloud (2004)

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



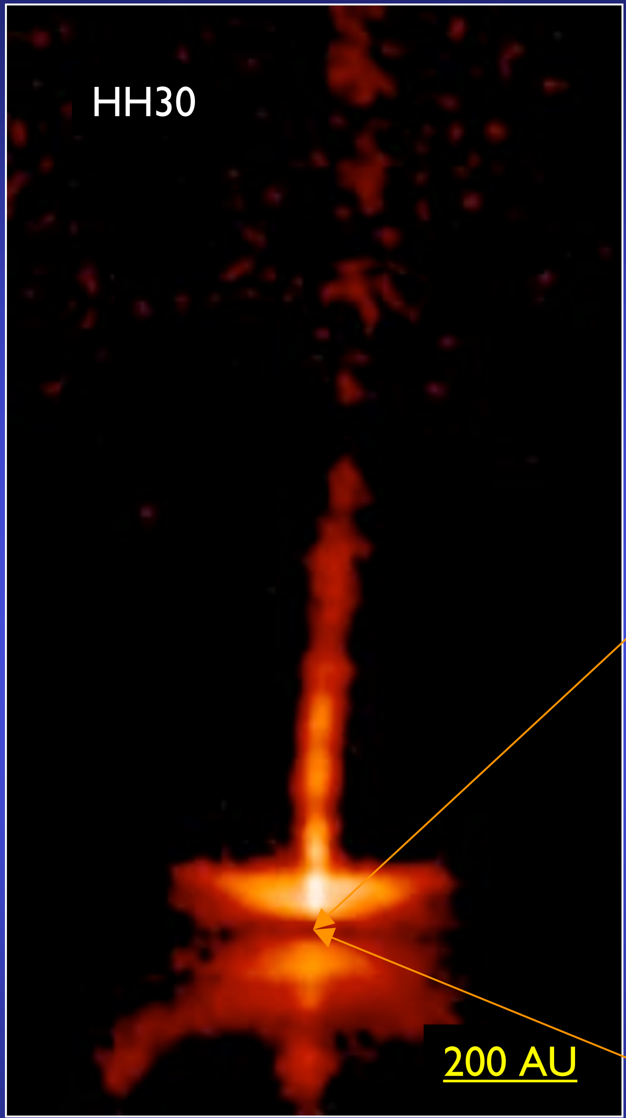


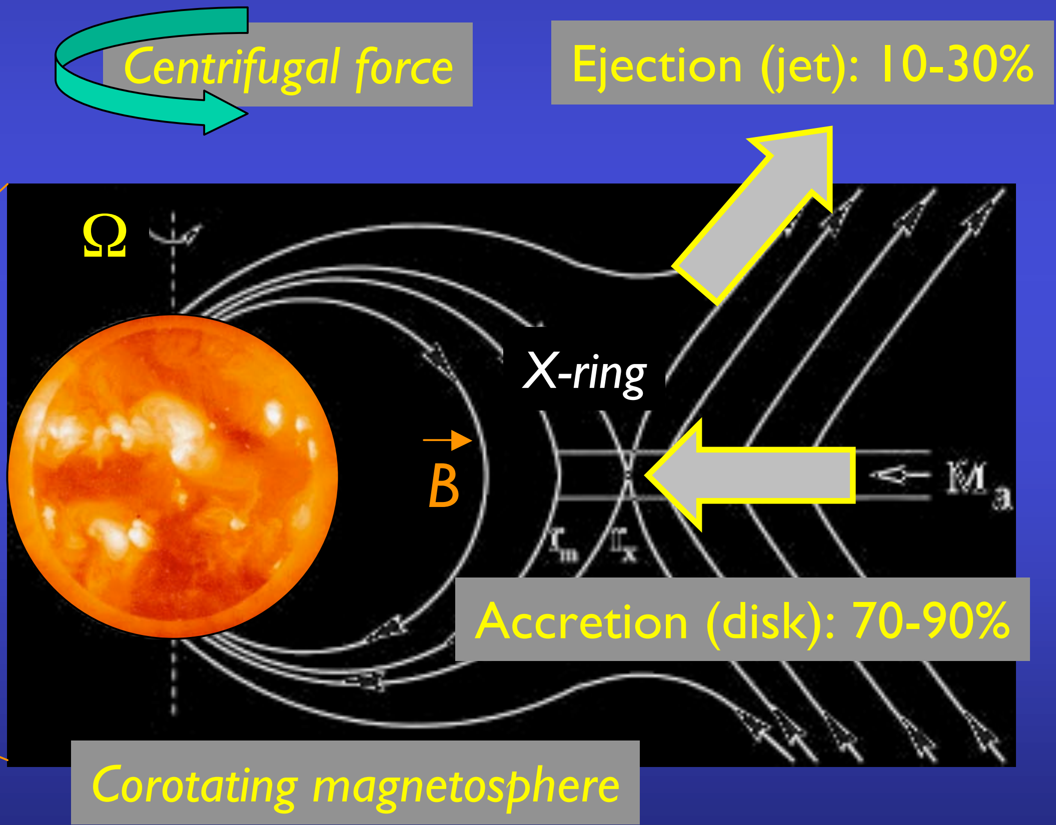
HST

MHD model for star-disk magnetic coupling

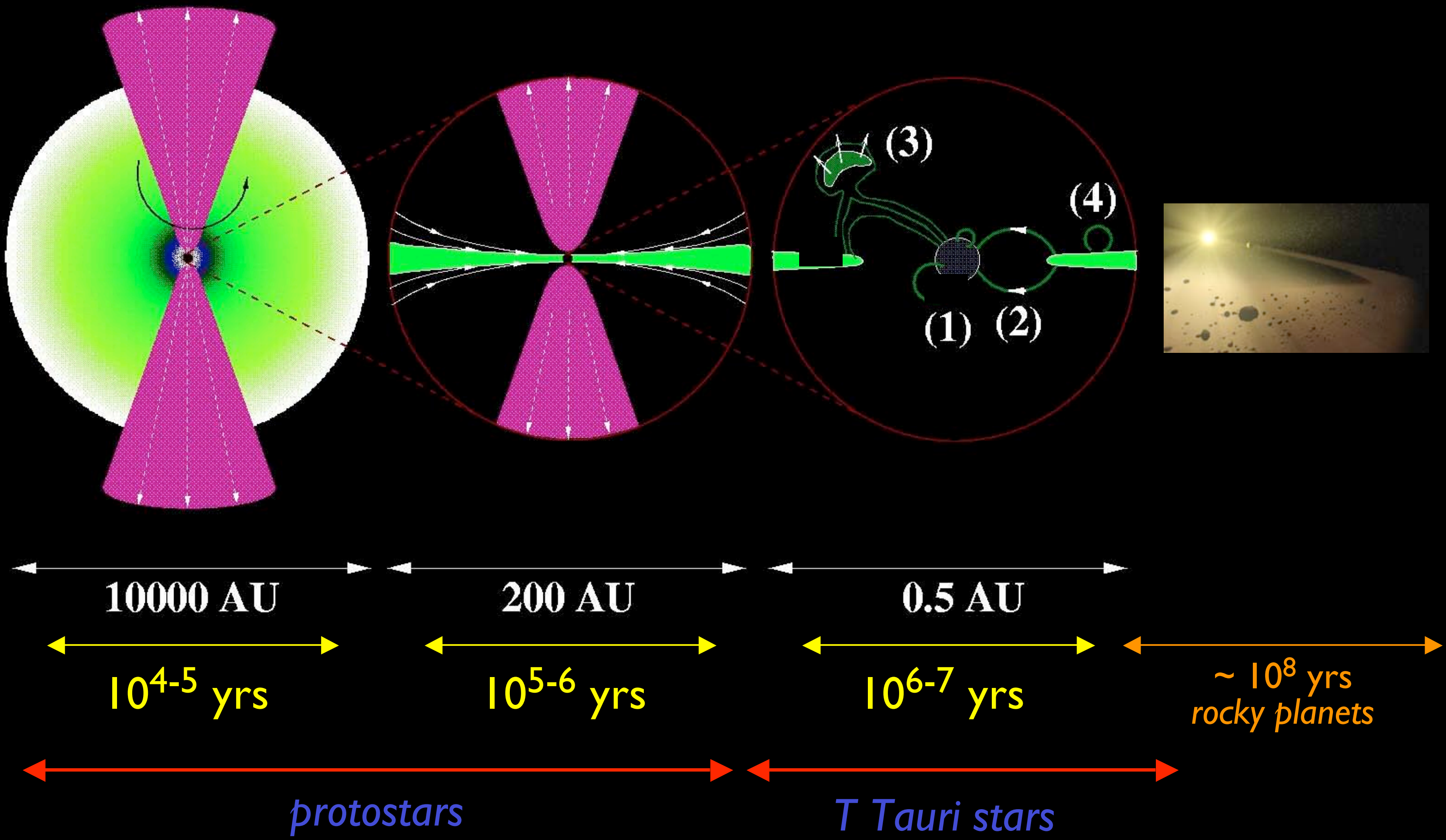
(J. Ferreira et al., 2001, ...)

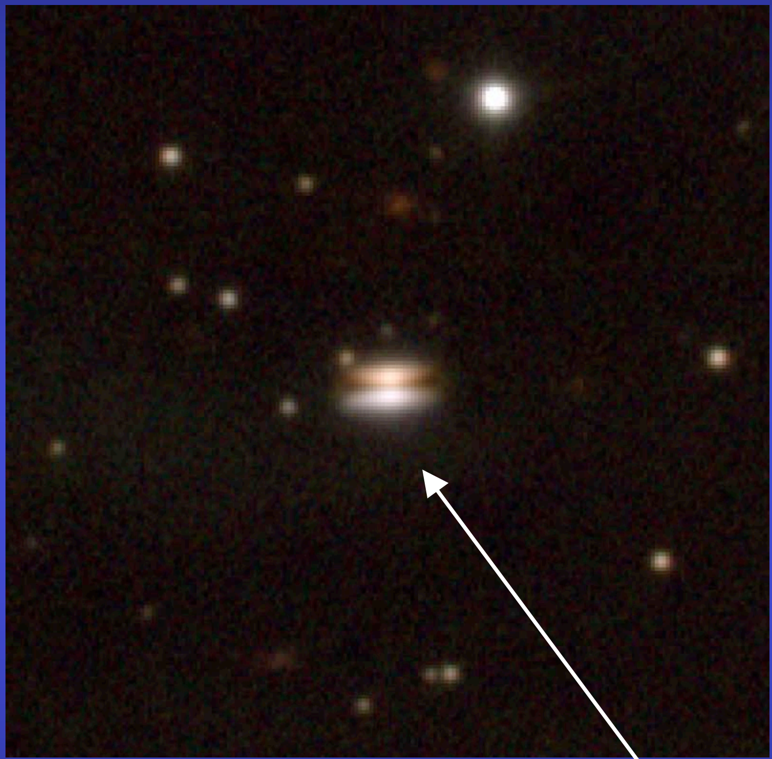
(Shu et al., Pudritz et al., Heyvaerts et al.,...)

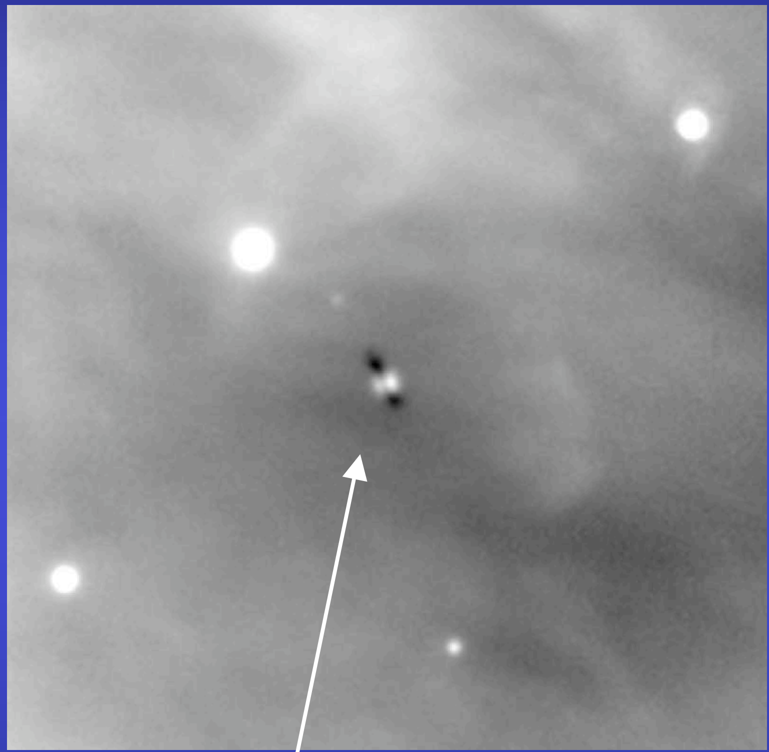




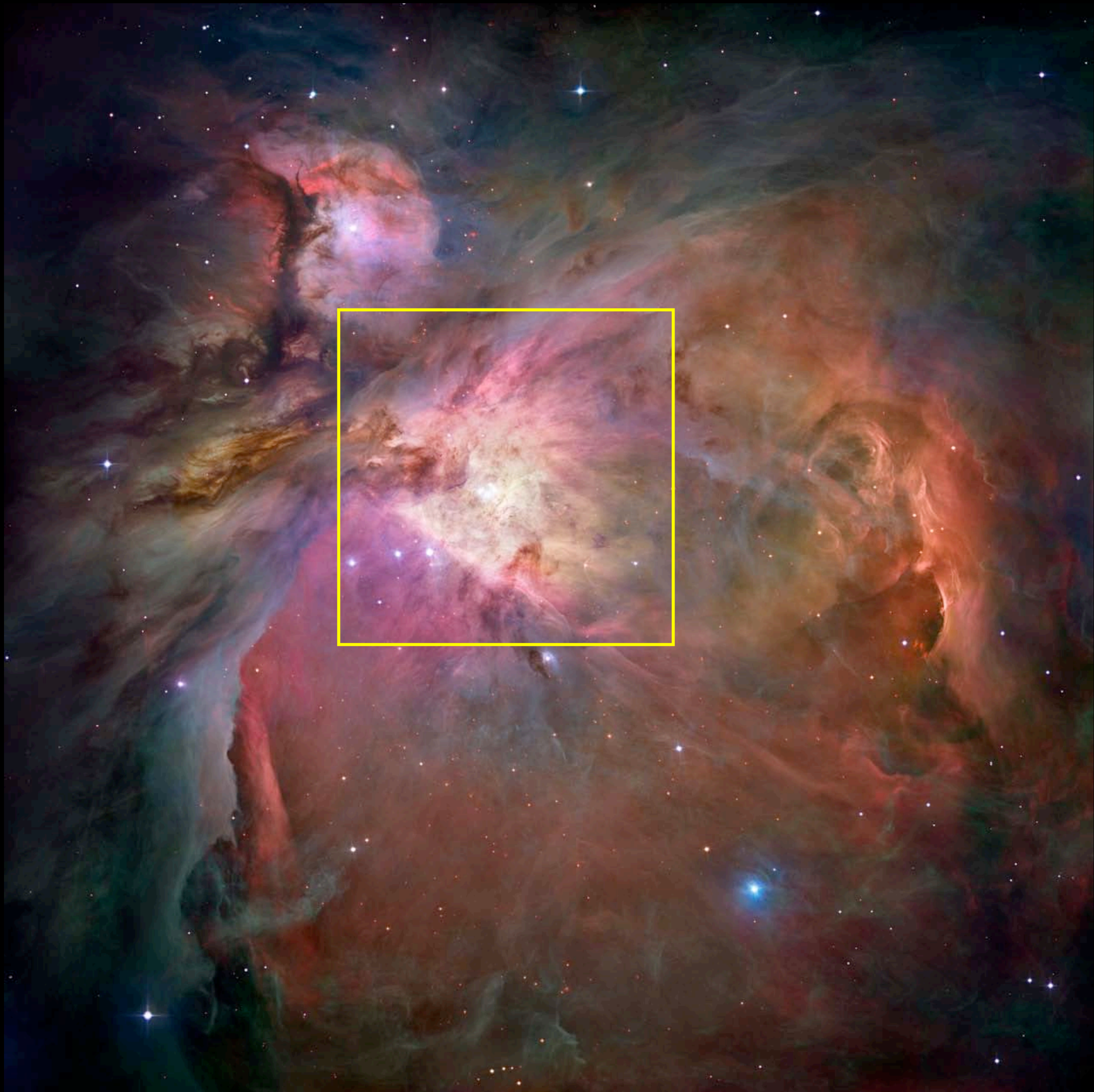
A brief history of early stellar evolution





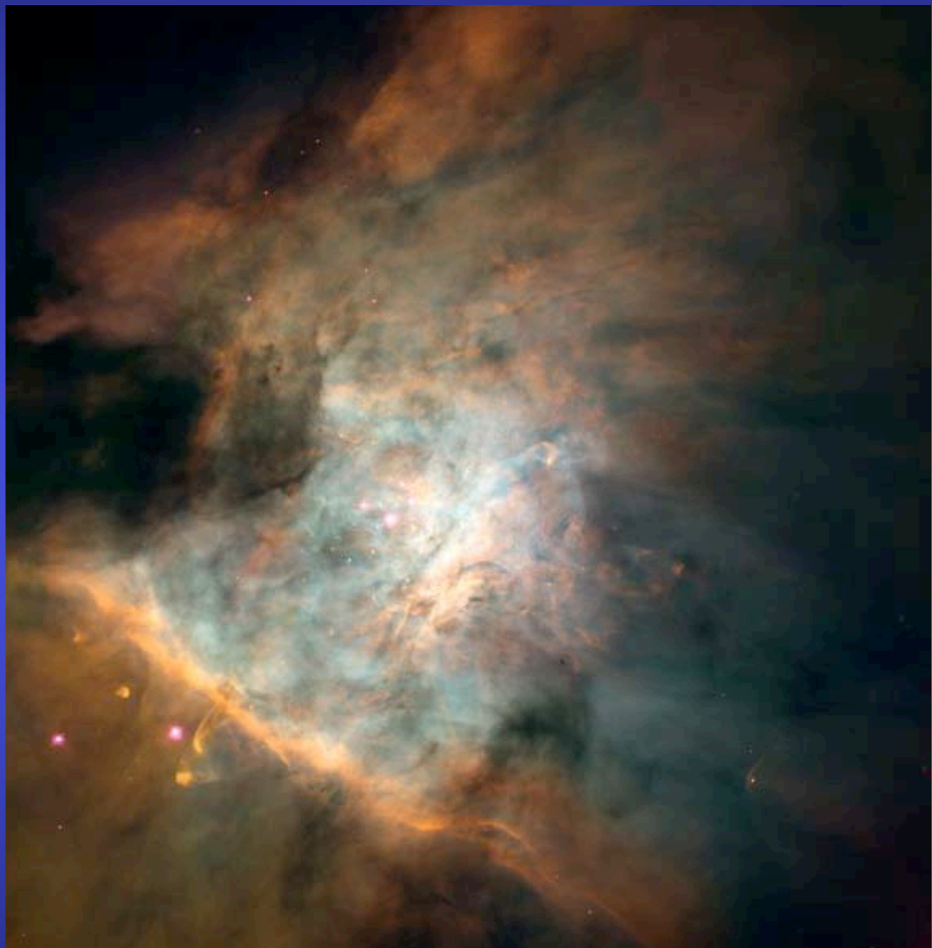


Was the Sun born here (ρ Oph) or there (Orion) ? Elsewhere ?

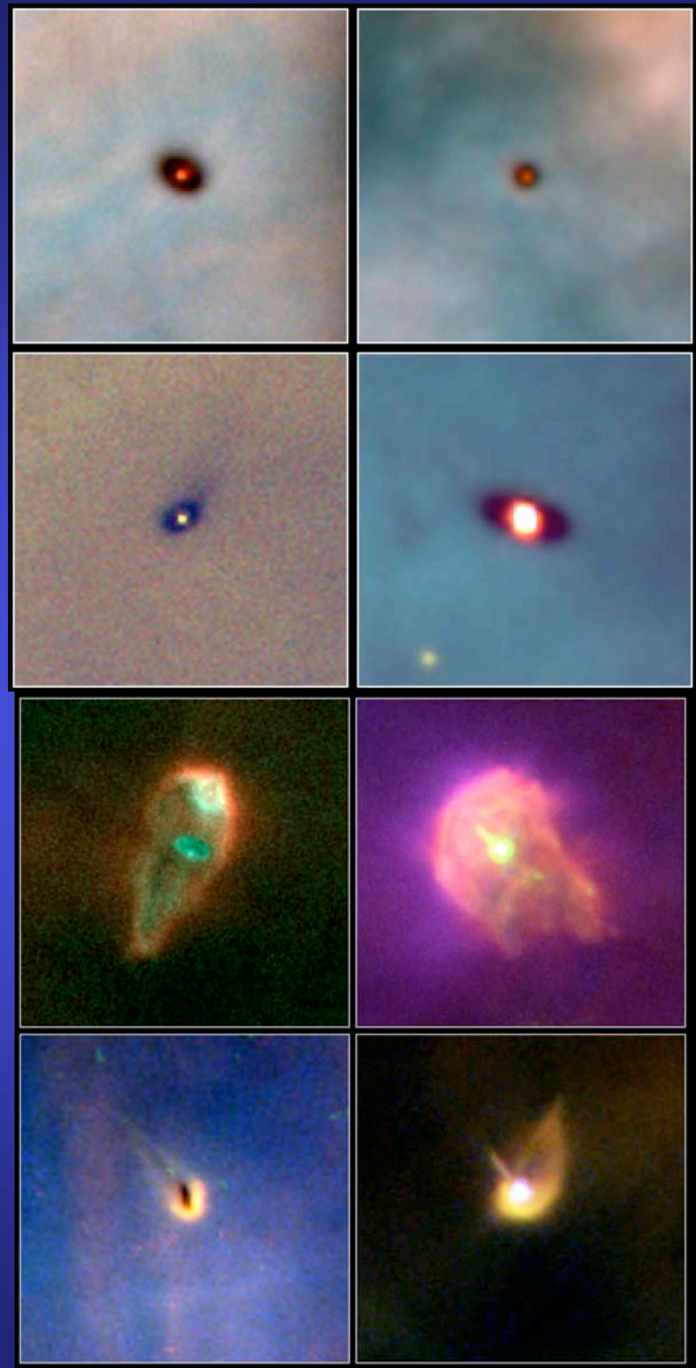


M42 and the Orion Nebula Cluster (HST, optical)

Zoom dans la nébuleuse d'Orion…



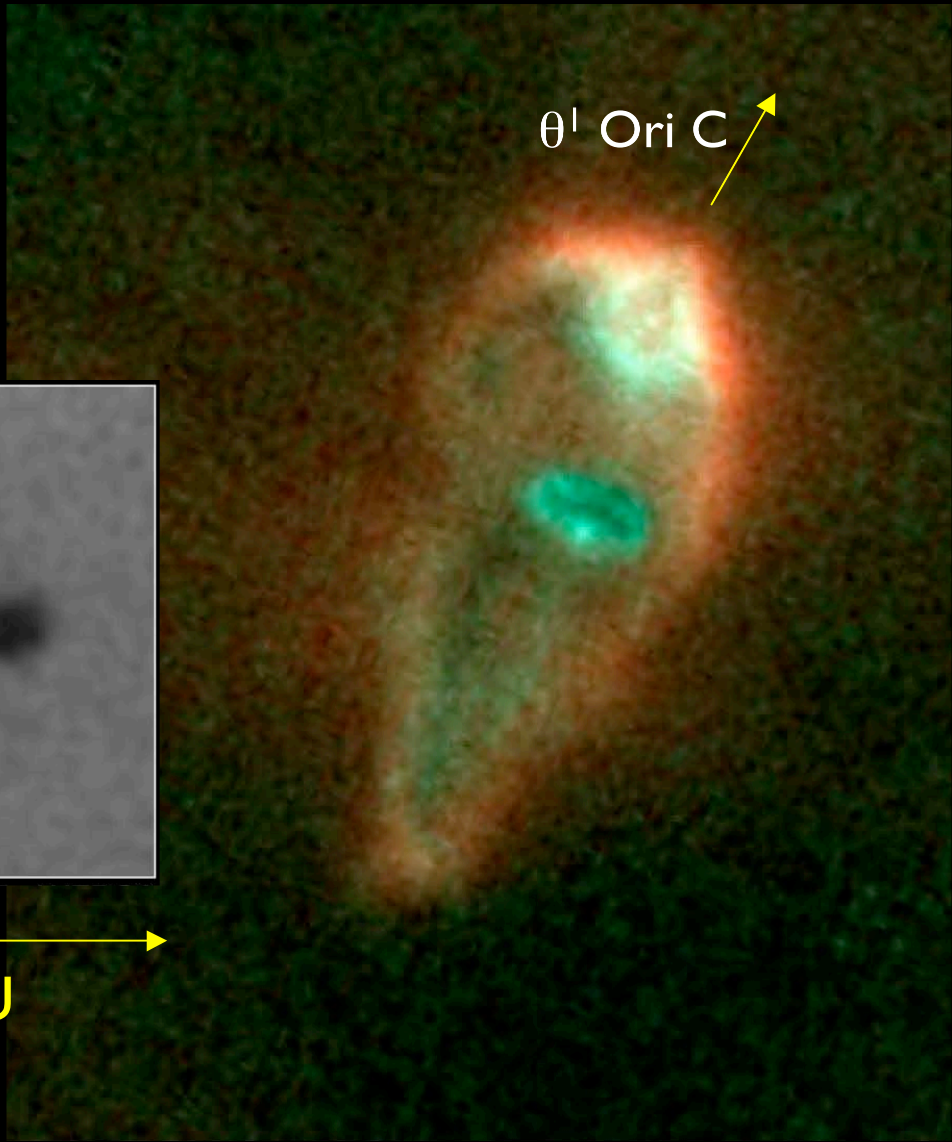
HST (Hubble)



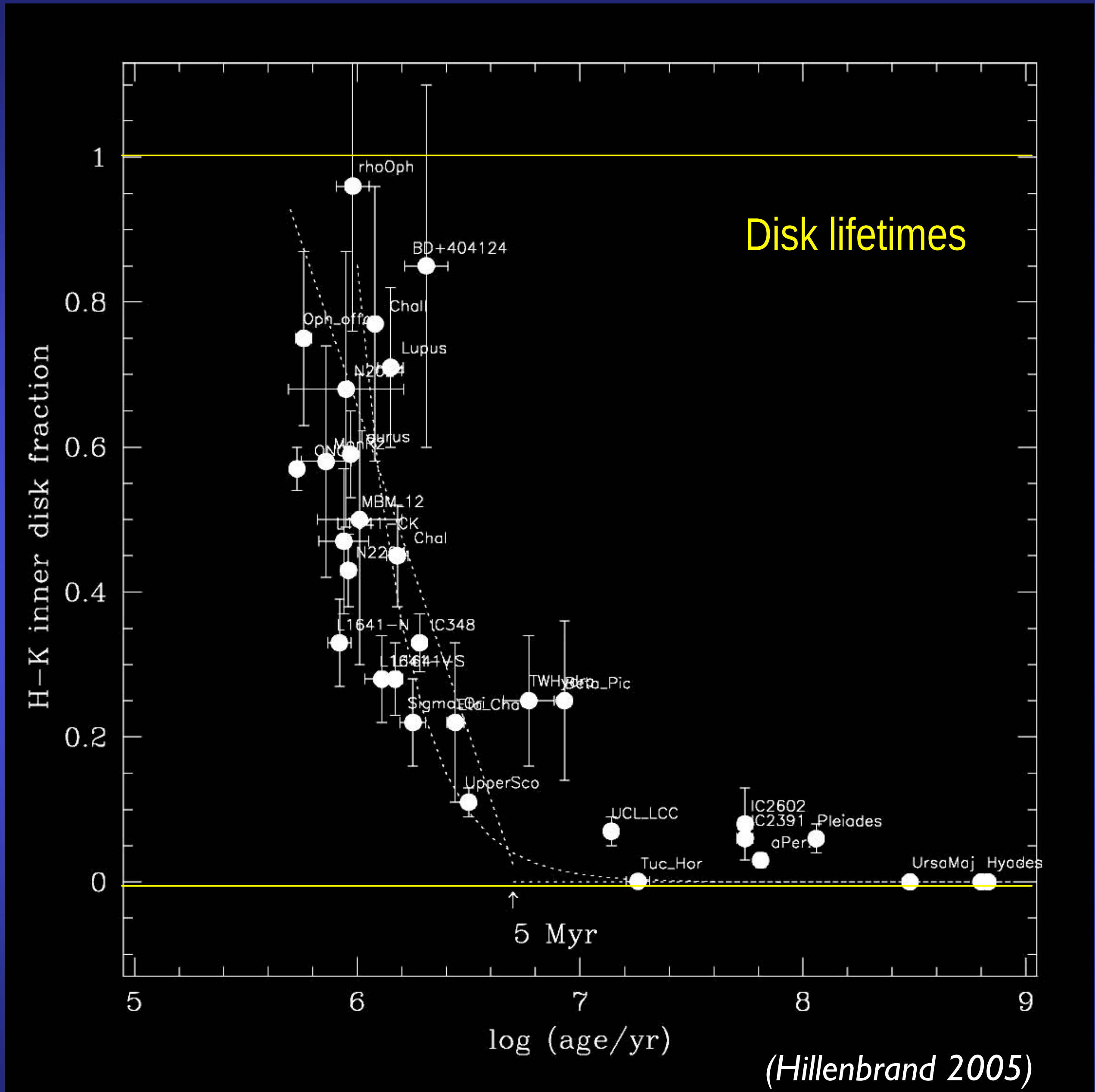
1995

2001

The Orion Nebula Cluster: UV irradiation => disk evaporation in ~ 1 Myr



500 AU

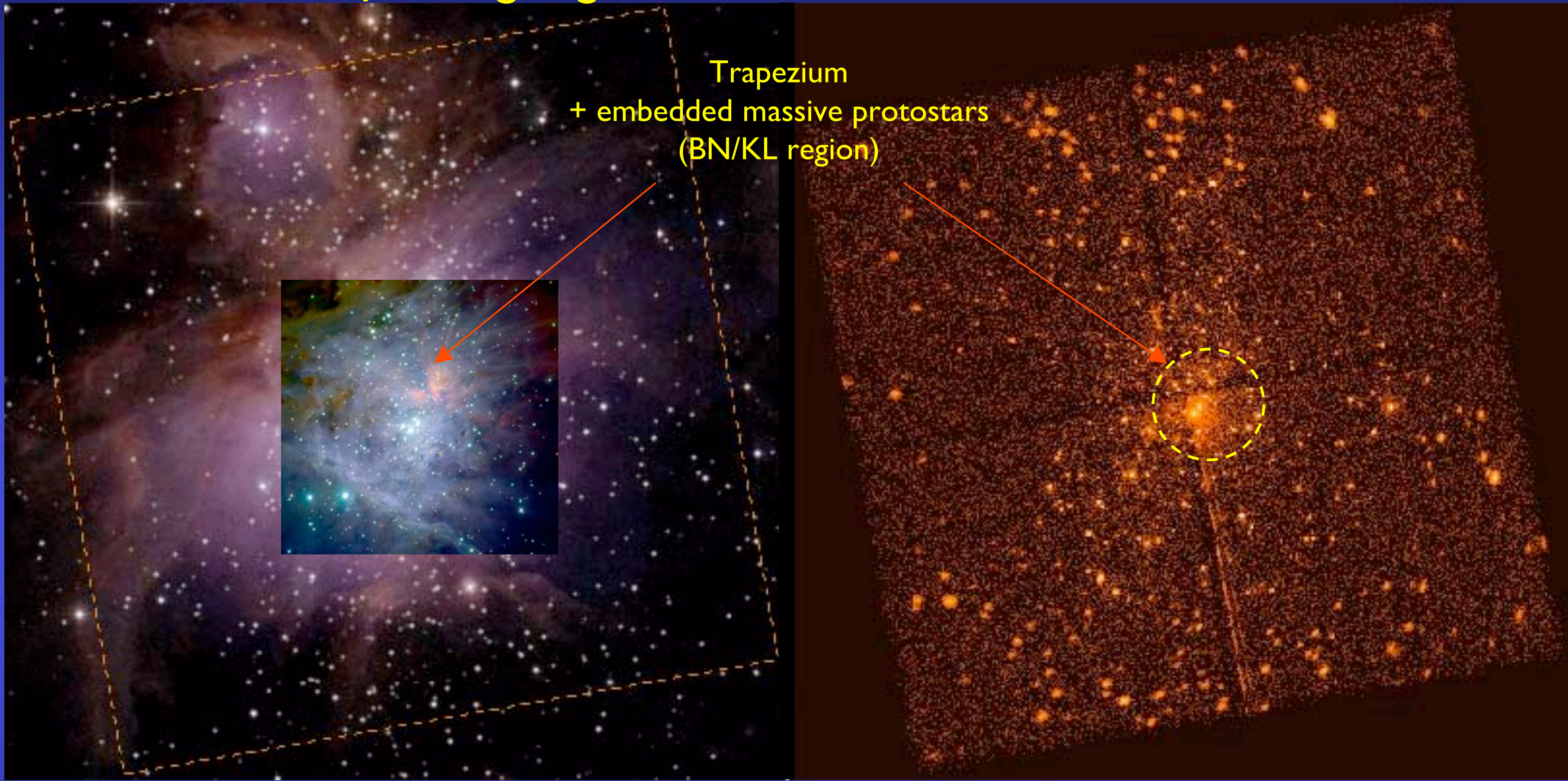


(Hillenbrand 2005)

2. Observer les régions de formation d'étoiles à haute énergie: les rayons X et le magnétisme stellaire

- L'universalité de l'émission X stellaire
  - L'activité magnétique
- L'irradiation des disques (étoiles de type solaire)
  - Rayons X et particules

Star forming regions: clusters and OB associations

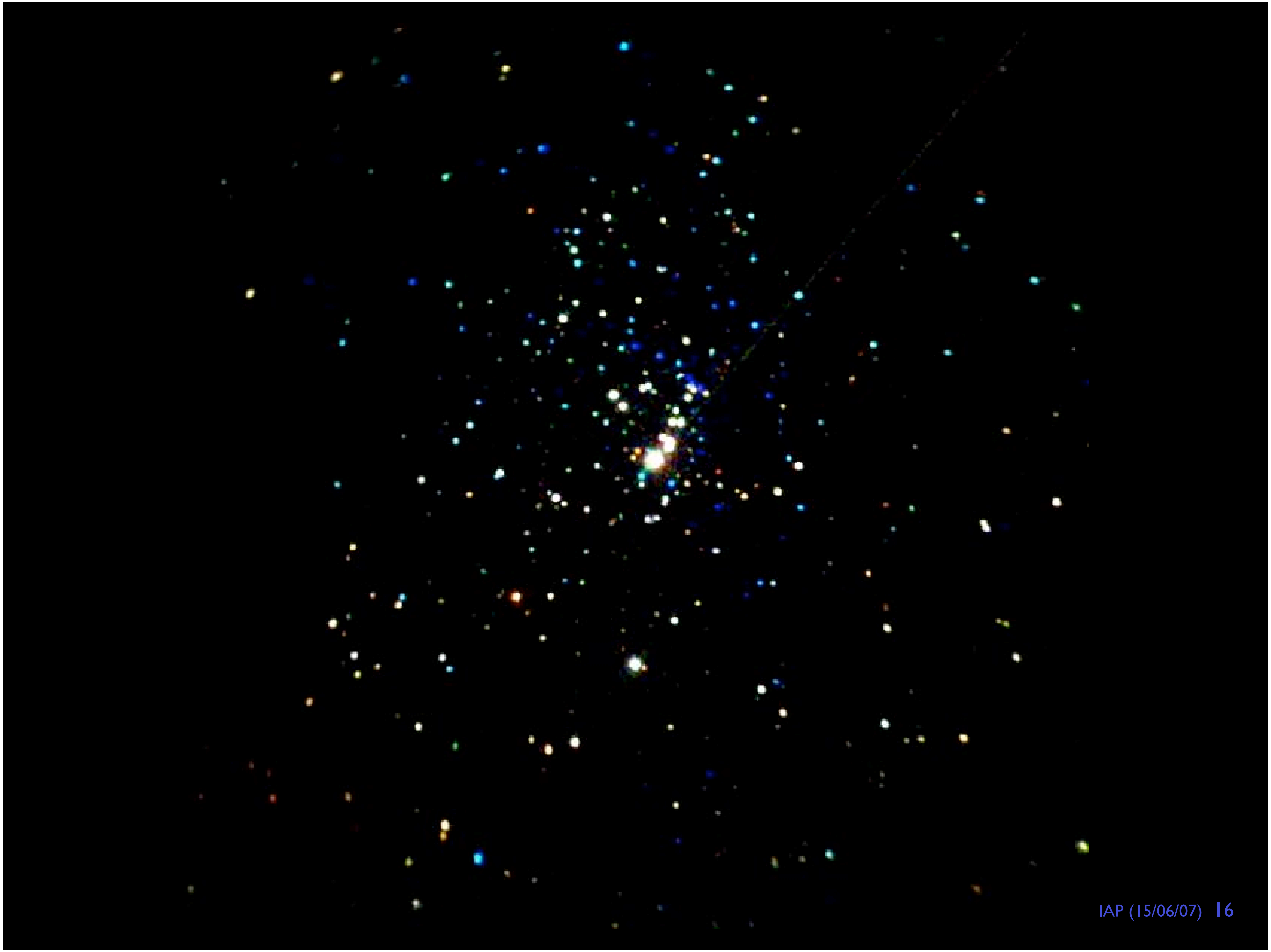


Near-IR image (2MASS + VLT) **X-ray image** (*Chandra* ACIS-I): Garmire et al. 2000

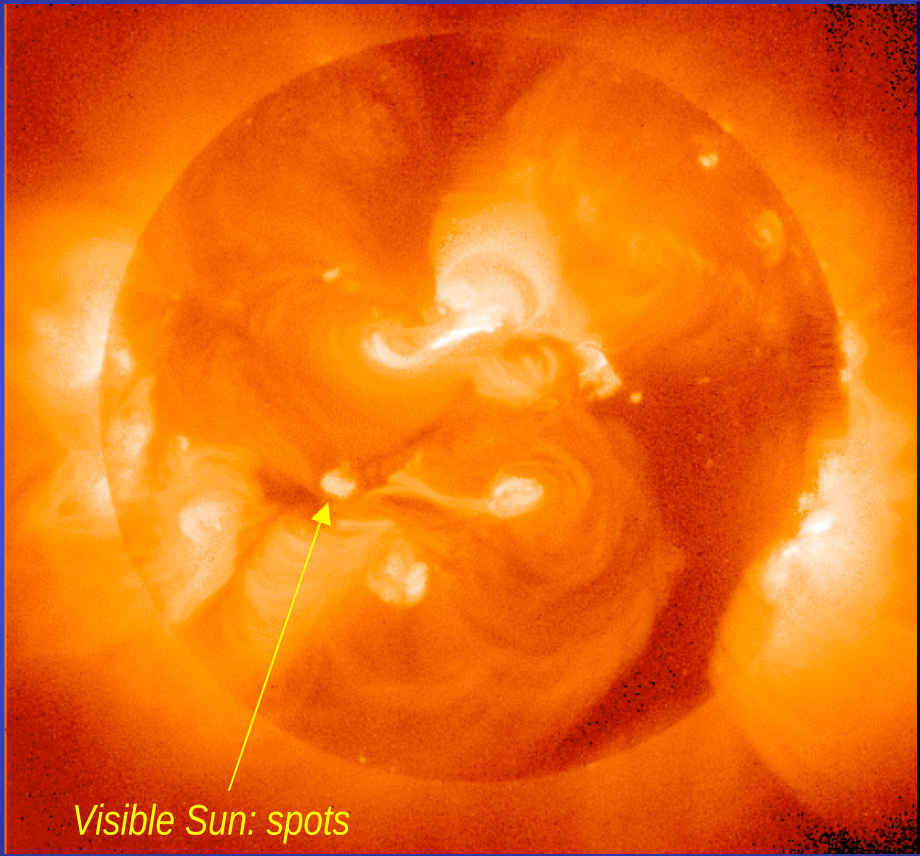
Orion Nebula (M42) and Trapezium region, O7+ (~ 17' x 17')

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

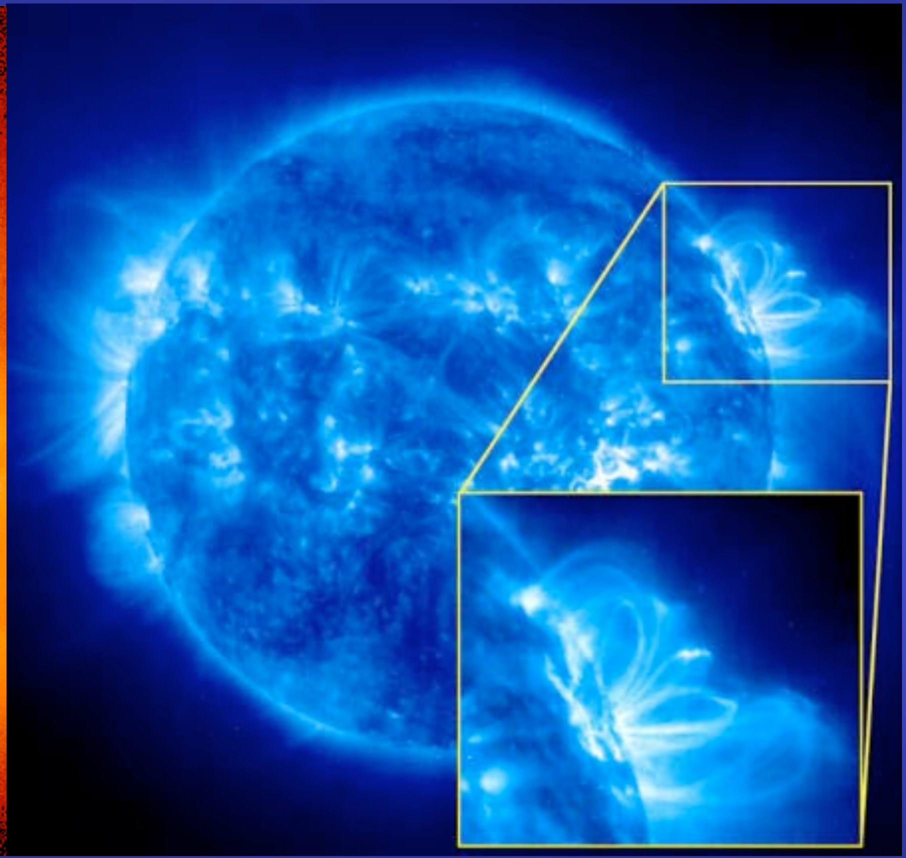
"COUP": Feigelson/McCaughrean (2005)



The young stars of Orion: "super-Suns"



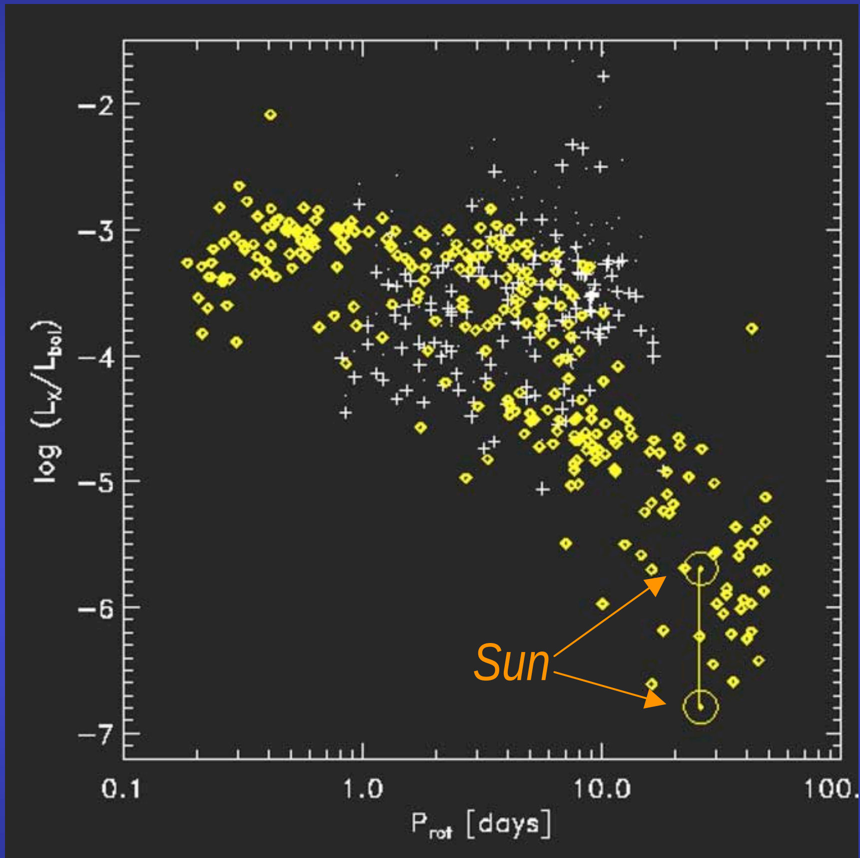
X-ray Sun (*Yohkoh* satellite)

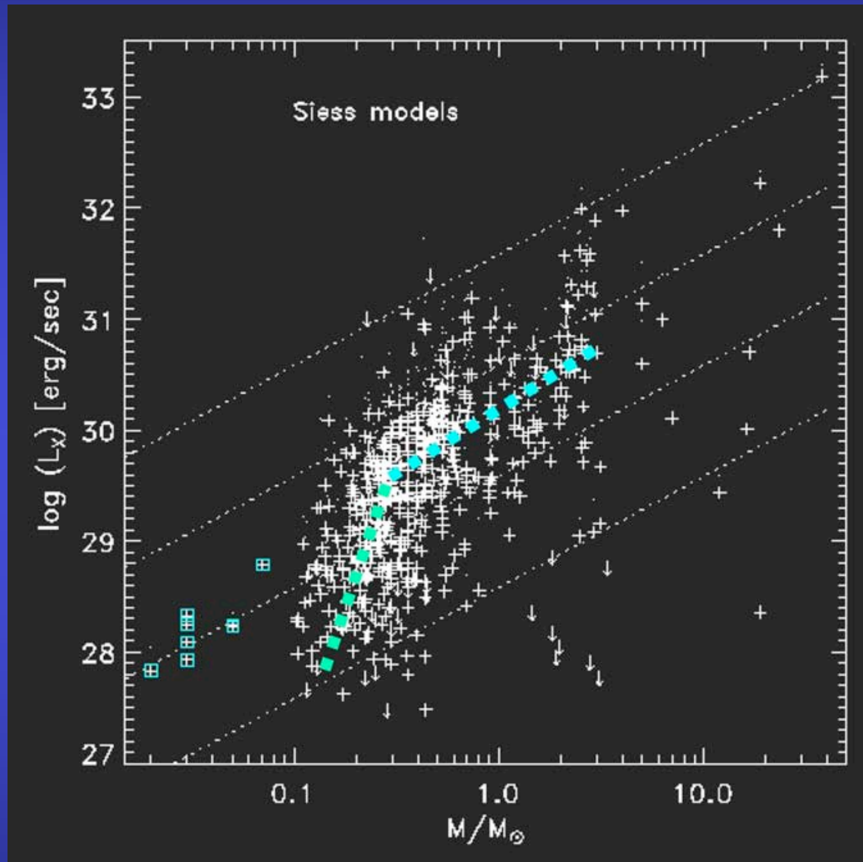


EUV Sun (SOHO satellite)

<=> convection-driven magnetic activity (flares)

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



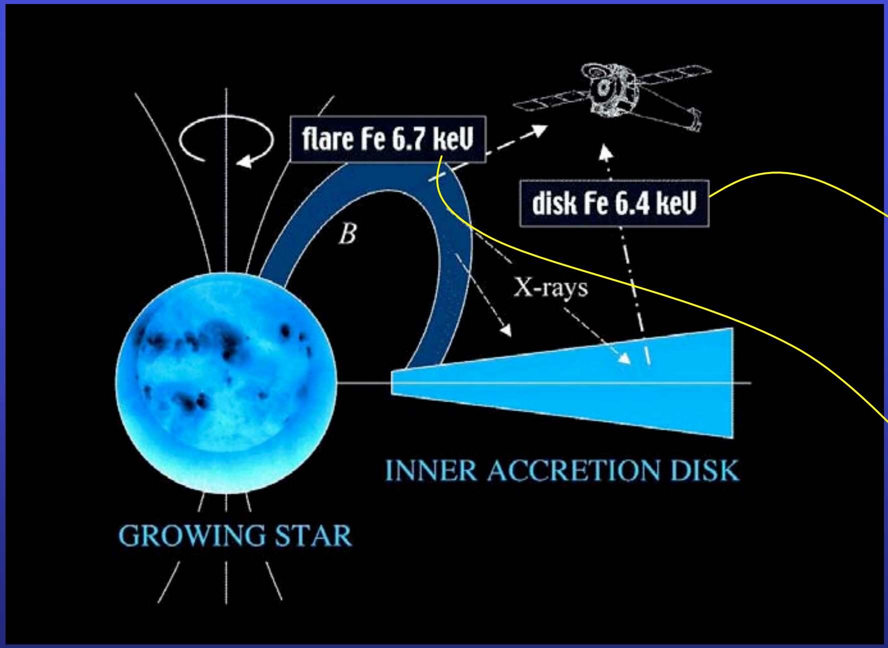


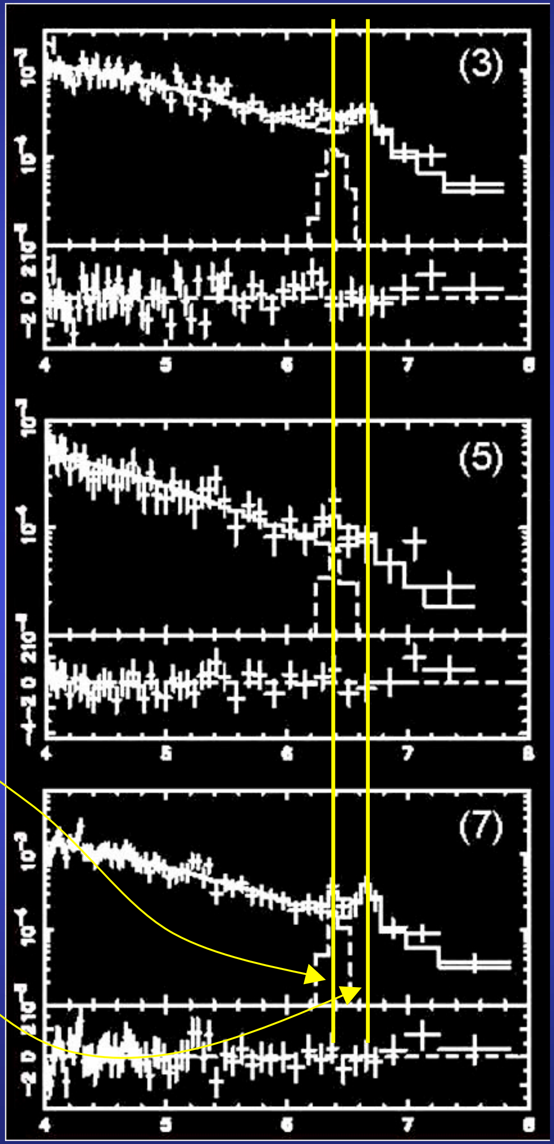
(Preibisch et al. 2005)

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

Fluorescing T Tauri stars in Orion…

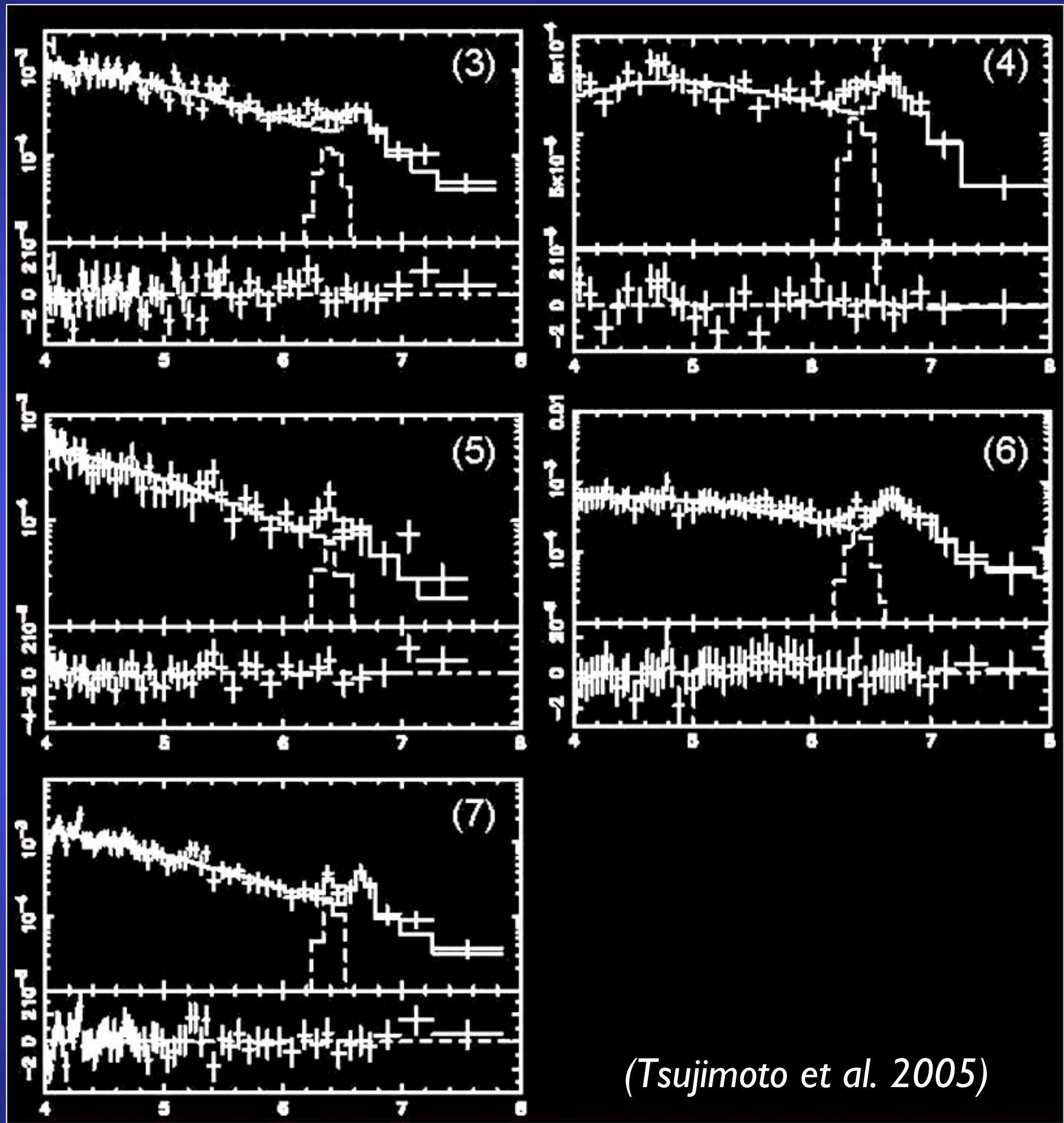
Fe line @ 6.4 keV => *Direct* evidence for disk irradiation; but special orientation required !
Other evidence for X-ray irradiation: Ne II 12 μm line (Glassgold et al. 2007; *Spitzer*)





(Chandra: *Tsujimoto et al. 2005*)

The Magnificent Seven: fluorescing sources in Orion…



See also El29 (Cl. I) in ρ Oph *(Favata et al. 2004)*

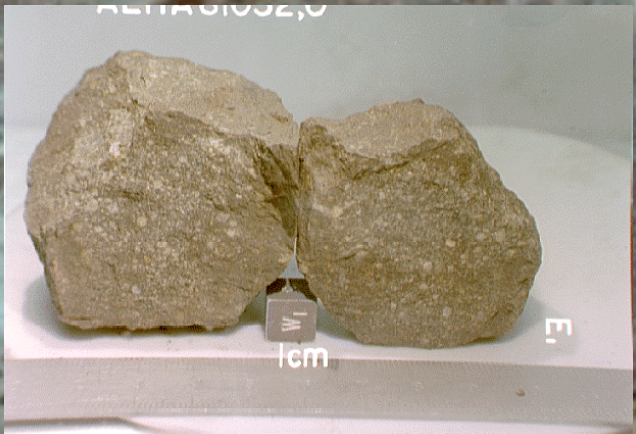
Line @ 6.4 keV => *Direct* evidence for disk irradiation

3. Les archives météoritiques et le berceau du Soleil

- Météorites = archives de la formation du système solaire (collisions entre "corps parents" primitifs: planétésimaux, asteroïdes)
- Les "radioactivités éteintes" dans les météorites
  - Sources possibles
- Débat: irradiation interne vs. contamination externe
  - Rayonnement cosmique galactique ?
- Présence d'une supernova !?
  - Est-ce fréquent, et/ou important pour le système solaire ?

Irradiation of the young solar system ?

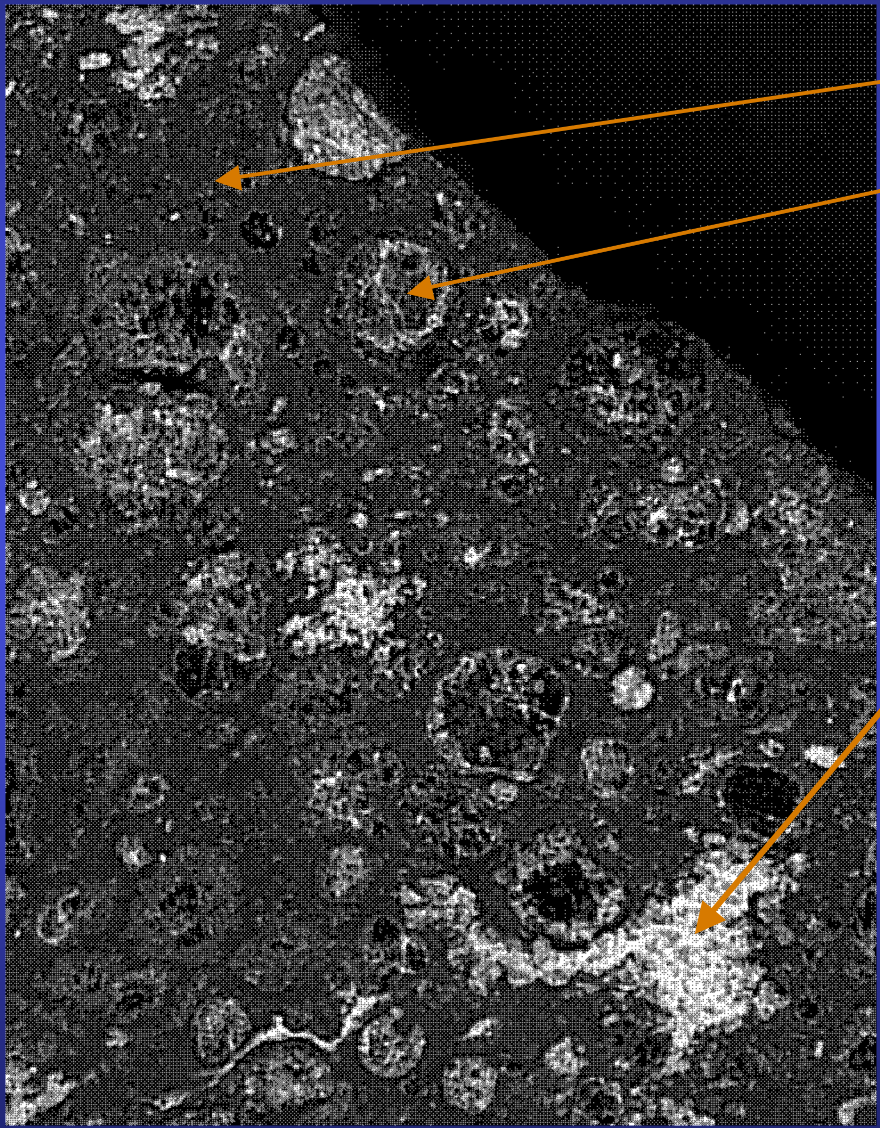
The legacy of meteorites



(Allende, Mexico, 1969)

Chondrites: the oldest objects in the solar system: 4.5672 ± 0.006 Gy

The "extinct" radioactivities problem in meteorites



Matrix

Chondritic grains

« Calcium-Aluminium (refractory) Inclusions» (CAIs): = radioactive disintegration of isotopes

^{7}Be ^{10}Be ^{26}Al ^{36}Cl ^{41}Ca ^{53}Mn ^{60}Fe

("extinct" radioactivities)

Gounelle, Chaussidon, Shu, et coll.

Allende

Radioactive Isotope (R)	T (Ma)	Daughter Isotope	Stable Isotope (S)	Objects
^{7}Be	52 days	^{7}Li	^{9}Be	CAIs
^{41}Ca	0.1	^{41}K	^{40}Ca	CAIs
^{26}Al	0.74	^{26}Mg	^{27}Al	CAIs, CHs, DIFF
^{10}Be	1.5	^{10}B	^{9}Be	CAIs
^{60}Fe	1.5	^{60}Ni	^{56}Fe	CAIs, DIFF
^{53}Mn	3.7	^{53}Cr	^{55}Mn	CAIs, CHs, DIFF
^{107}Pd	6.5	^{107}Ag	^{108}Pd	DIFF
^{182}Hf	9	^{182}W	^{180}Hf	CHs, DIFF
^{129}I	16	^{129}Xe	^{127}I	CAIs, CHs, DIFF
^{92}Nb	36	^{92}Zr	^{93}Nb	CHs, DIFF
^{244}Pu	81	Fission products	^{238}U	CAIs, DIFF
^{146}Sm	103	^{142}Nd	^{144}Sm	DIFF

Extinct radioactivities (τ ~ a few Myr)
In the young solar system

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

Recent discovery: ^{7}Be T = 53 days, Ab. ~ 9×10^{-7}

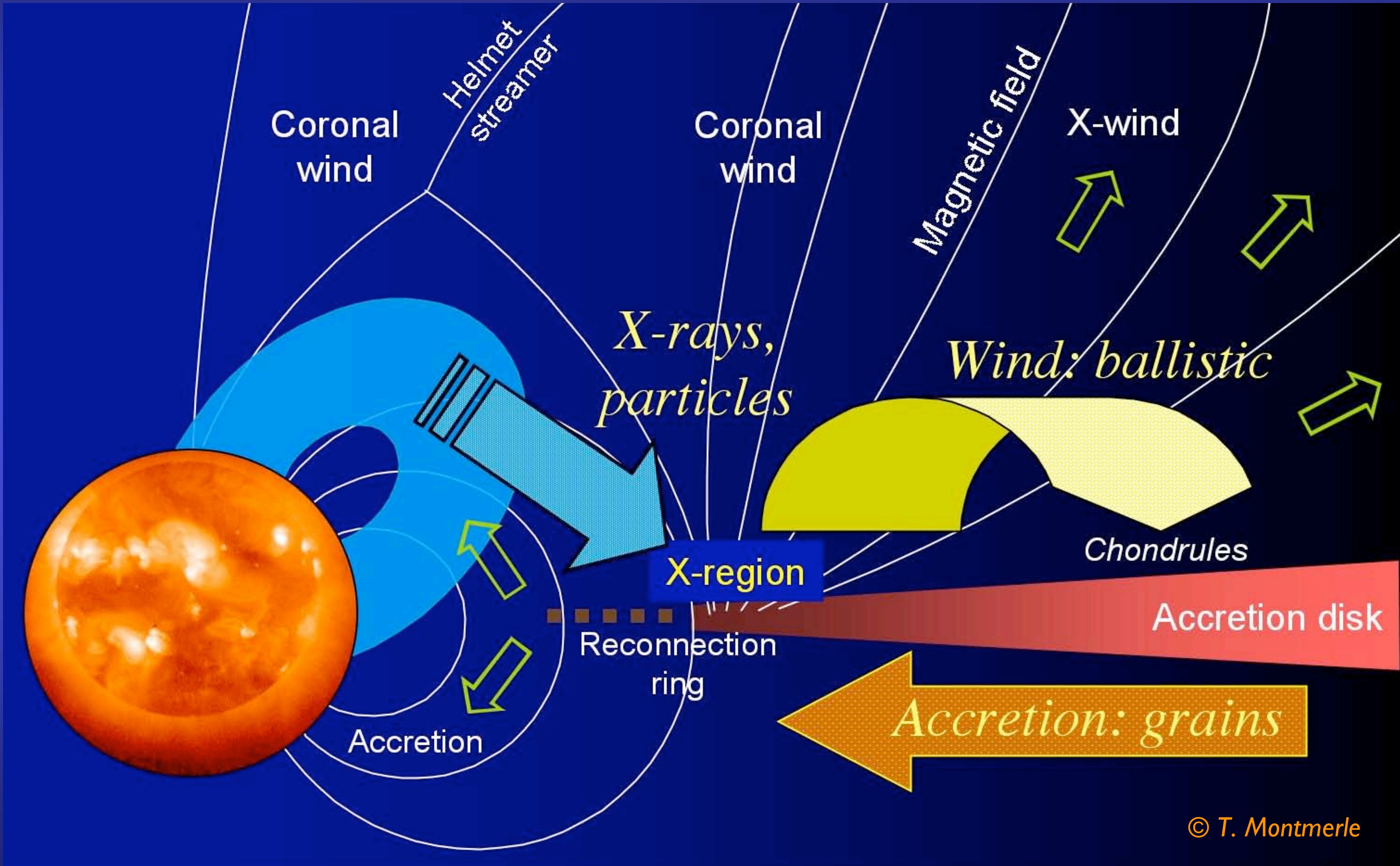
Chaussidon et al. 2004
(*) Mostefaoui et al. 2005, Bizzarro et al 2007.

Formation mechanisms

- Light elements: spallation reactions only (= in-flight nuclear collisions)
  - *^{7}Be, ^{10}Be*
- Spallation reactions and/or regular massive star nucleosynthesis
  - ^{26}Al, ^{36}Cl, ^{41}Ca, ^{53}Mn
- Explosive nucleosynthesis
  - *^{60}Fe* => neutron excess, signature of supernovae !

- *^{26}Al and ^{60}Fe are the only "extinct radioactivity" isotopes to decay via γ-ray emission (resp. 1.809 MeV and 1.174 MeV)*
  - => they can be observed (from space) in distant regions

An attractive (but controversial) comprehensive model (except for ^{60}Fe): the "X-wind" model of Shu et coll.



Irradiation of the"primitive nebula"

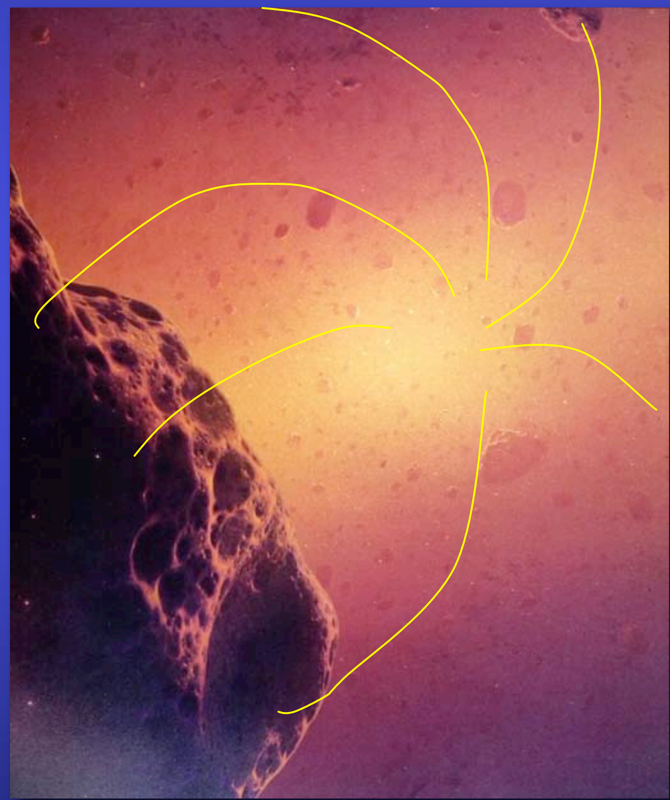
- X-ray flares : *analogy with the Sun*

⇒ irradiation of dust grains (Si, Ca, C, O…) by low-energy particles (p, ^3He, ^4He)

=> *Spallation nuclear reactions*

are able to solve all the extinct radioactivities

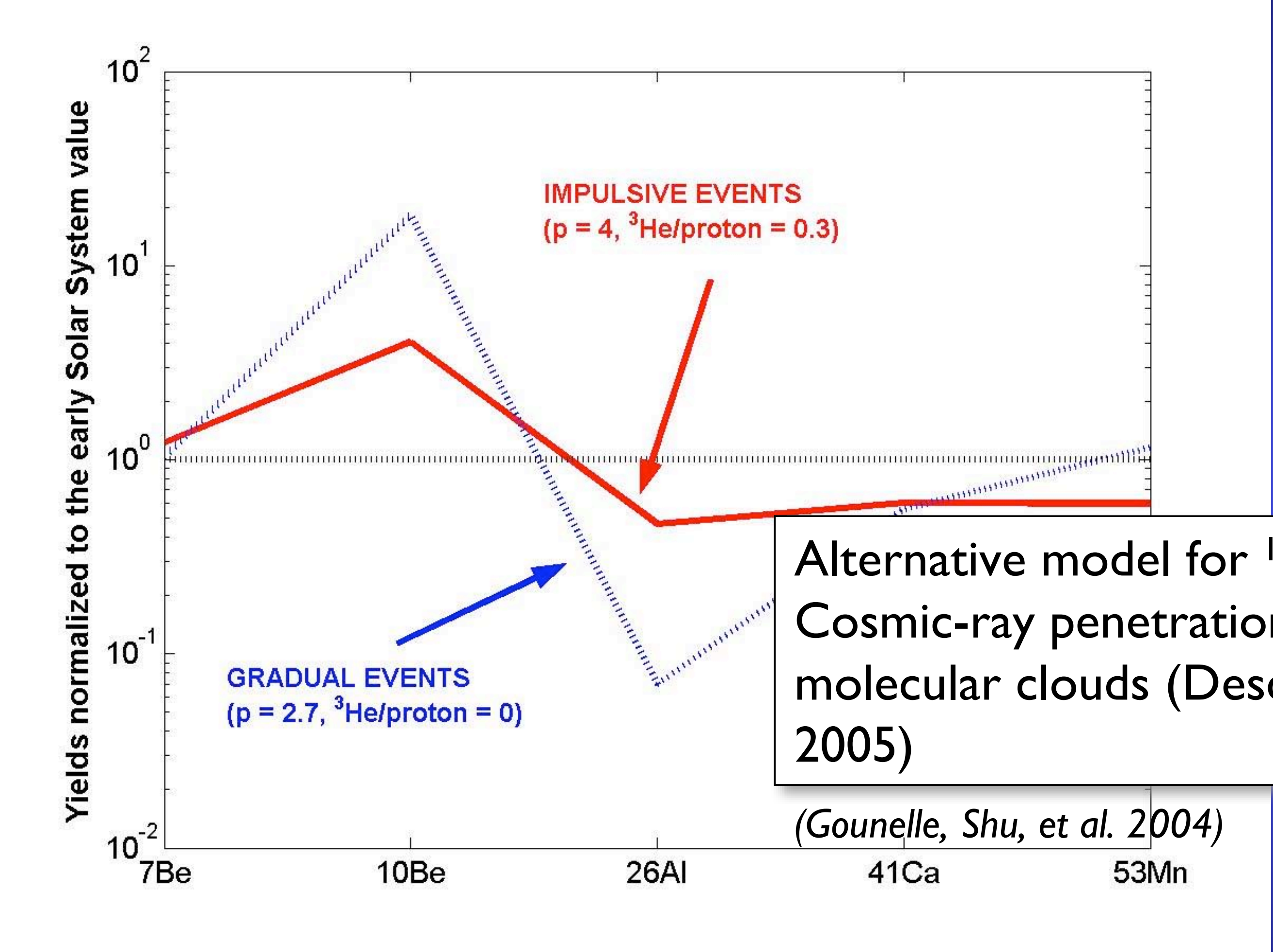
EXCEPT ^{60}Fe: *Supernova ???*



OK for the young Sun, if magnetic activity (X-rays) enhanced by ~ 10^4 - 10^5:

This is observed in Orion !

Irradiation model, scaled to X-ray flares



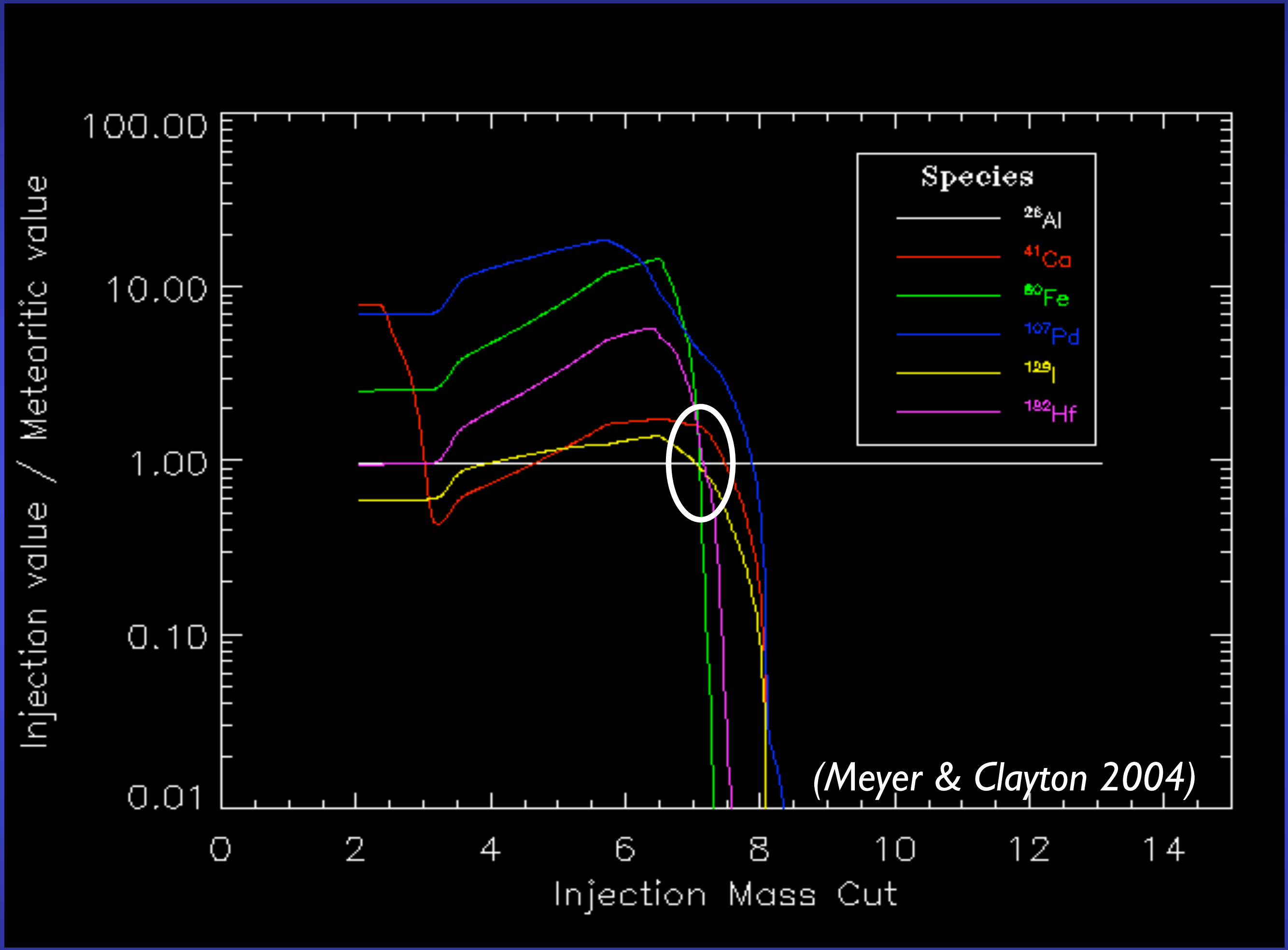
Alternative model for ^{10}Be only: Cosmic-ray penetration of molecular clouds (Desch et al. 2005)

(Gounelle, Shu, et al. 2004)

⇒ Can explain all nuclides, except ^{60}Fe; ***generic***

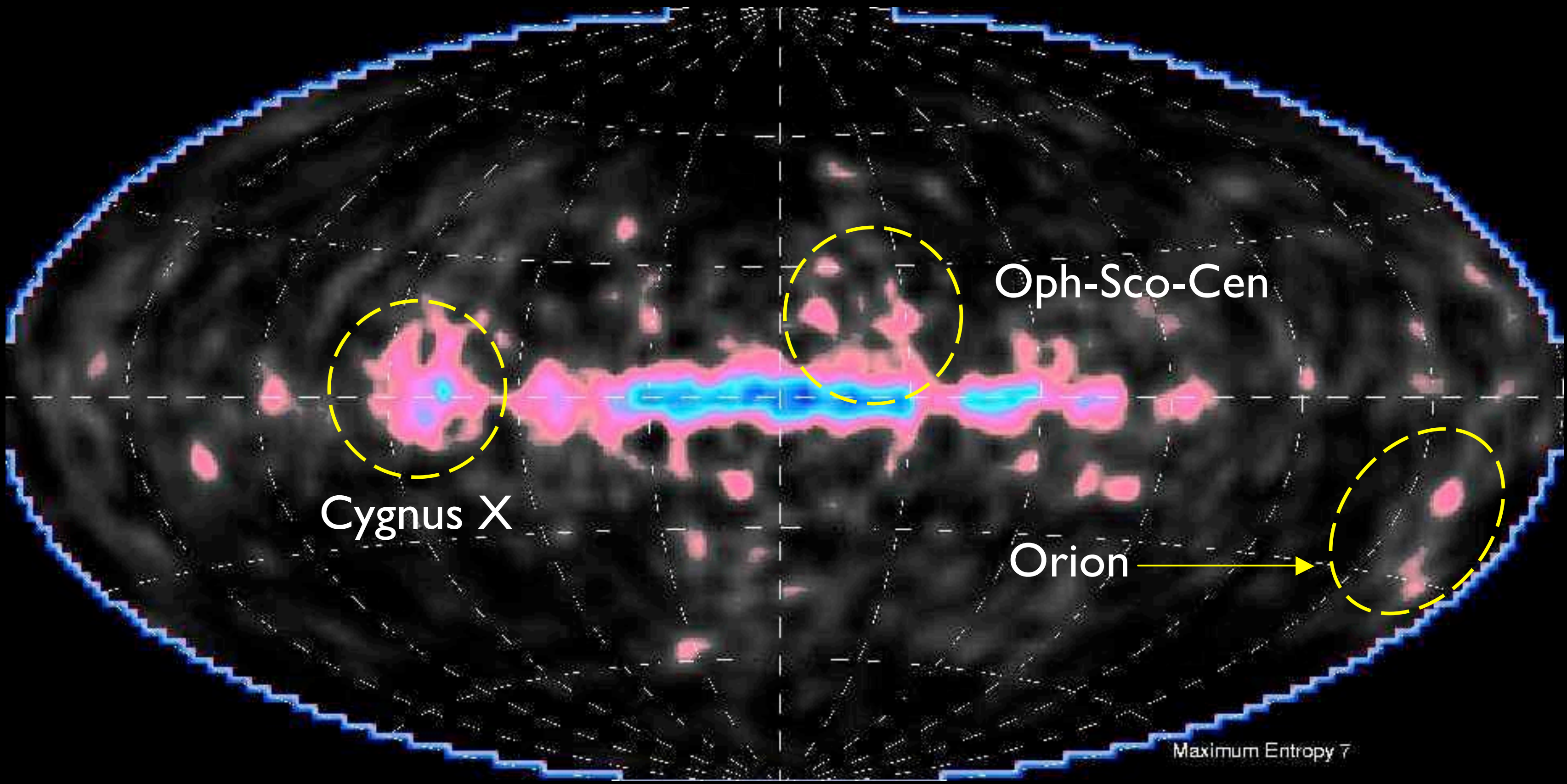
(i.e., works for *all solar-like stars* and *all star-forming regions*)

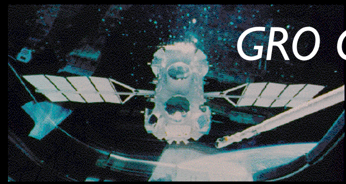
Nearby SNII injection model



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

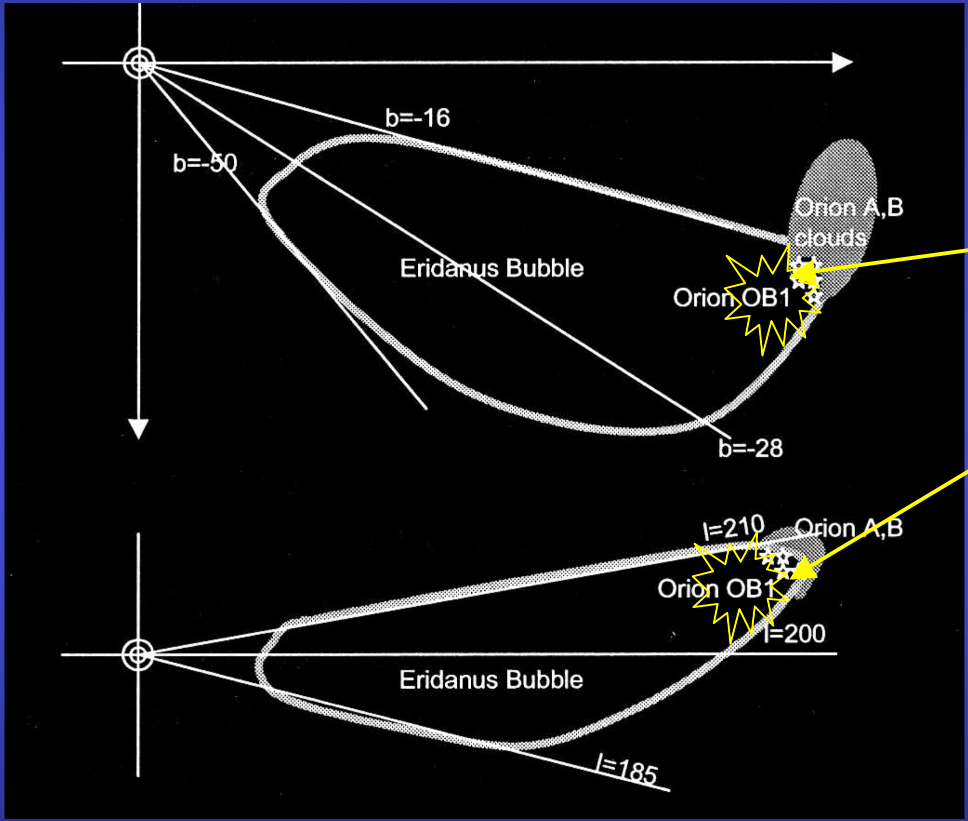
Ubiquitous live ^{26}Al: The Milky Way @ 1.809 MeV



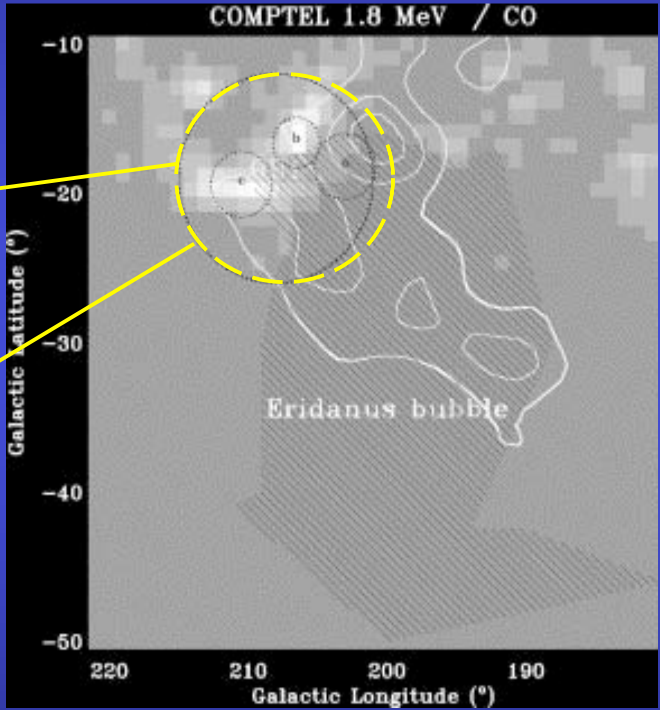


GRO Comptel (2001)

The "one-million-year" Orion ^{26}Al emission from massive stars:
"contamination" *at the edge of the molecular cloud*



The Eridanus Superbubble

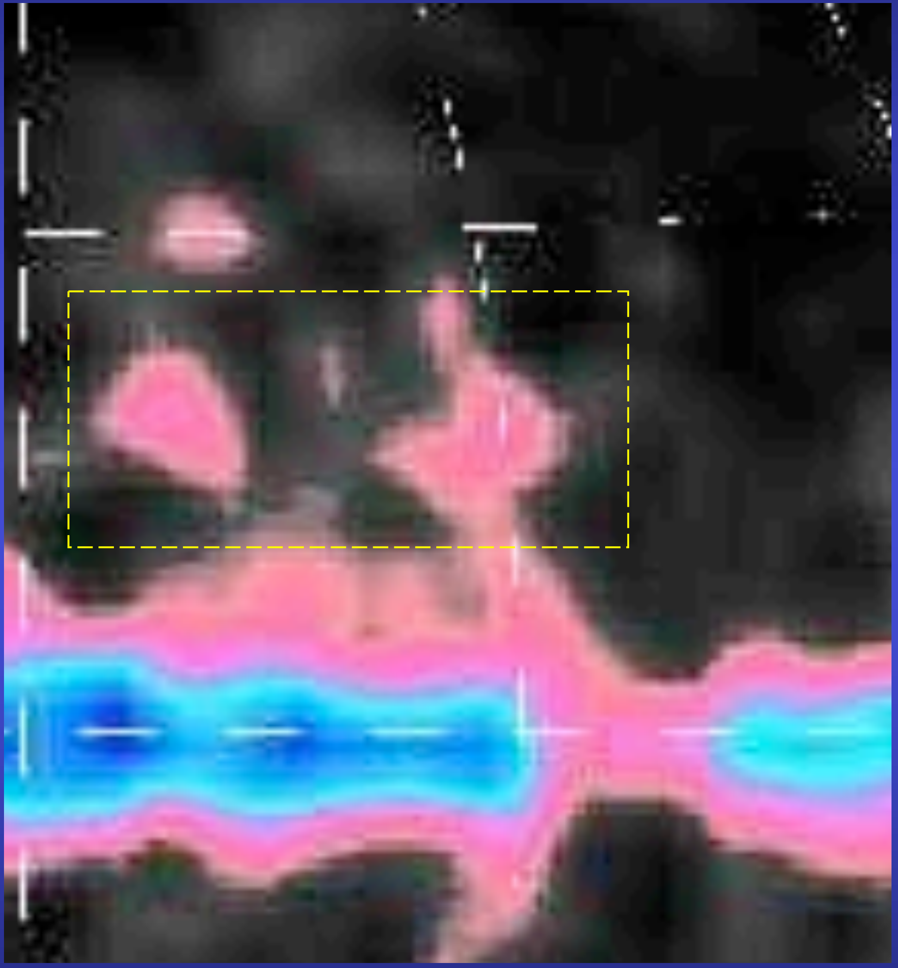


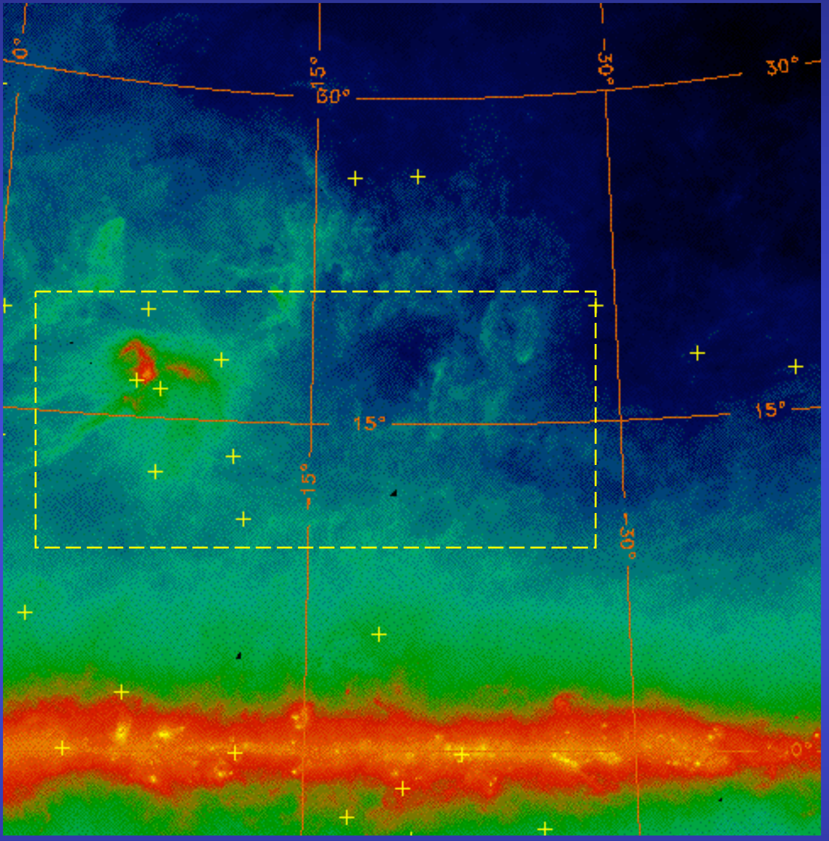
1.809 MeV *(Diehl et al. 2002)*

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

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

winds from (background) massive stars



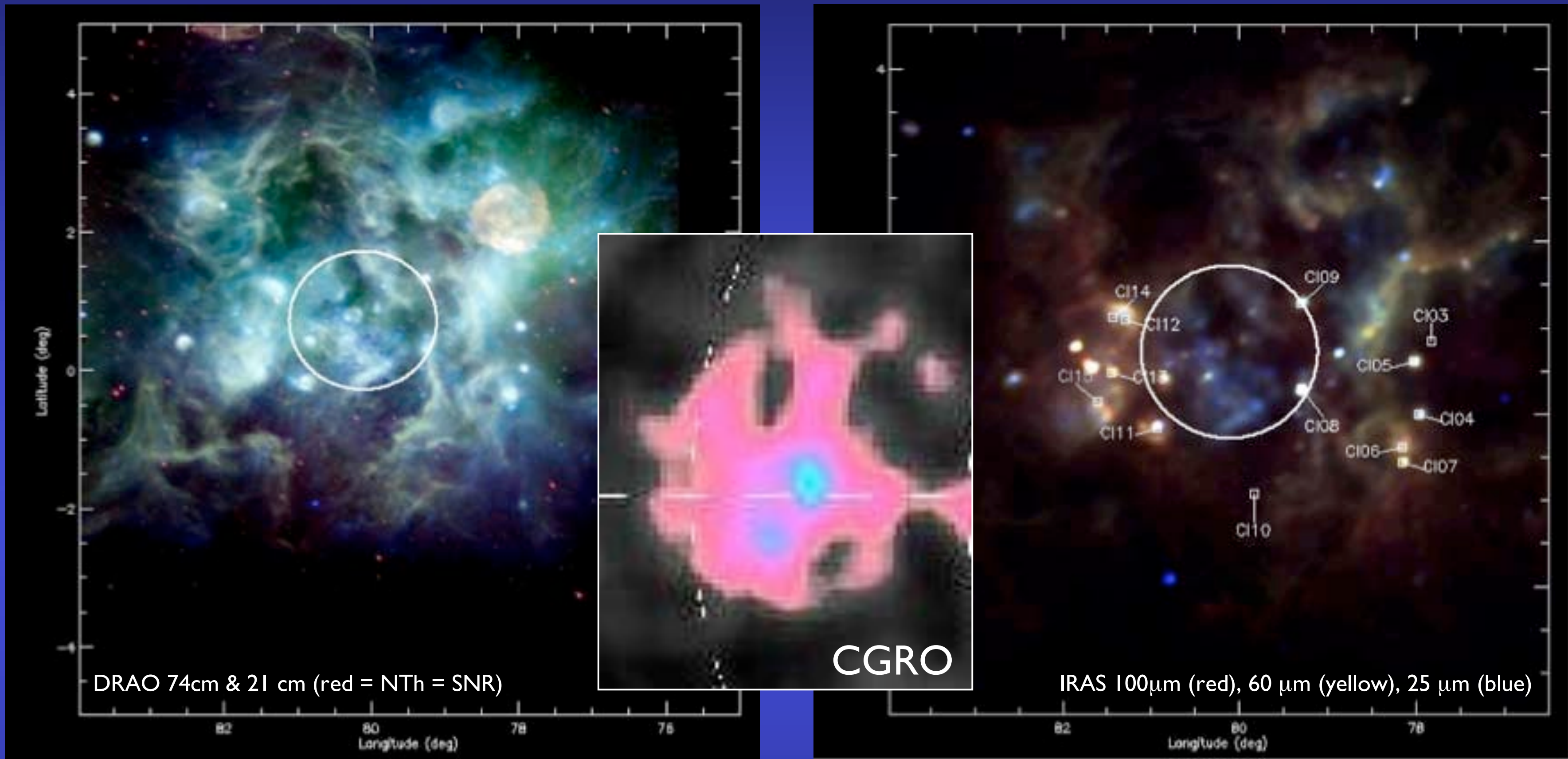


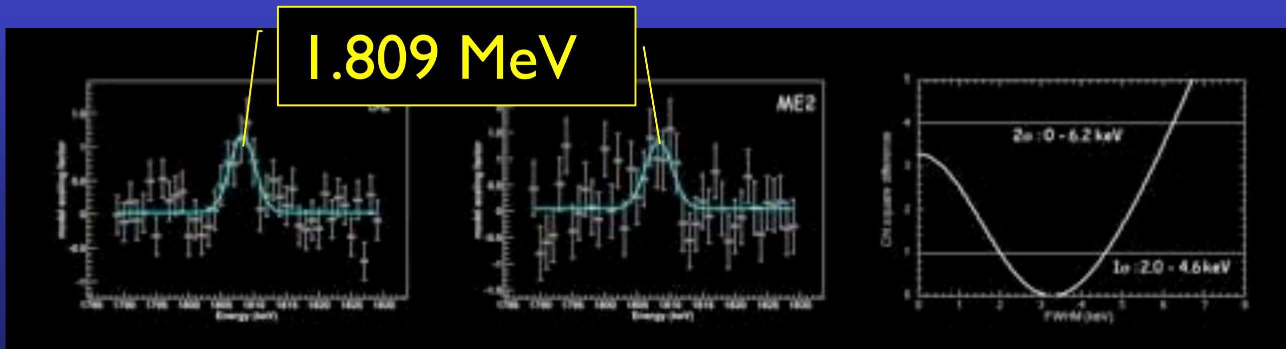
IRAS 100 μm

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

(Montmerle 2002)

The Cygnus X ^{26}Al emission

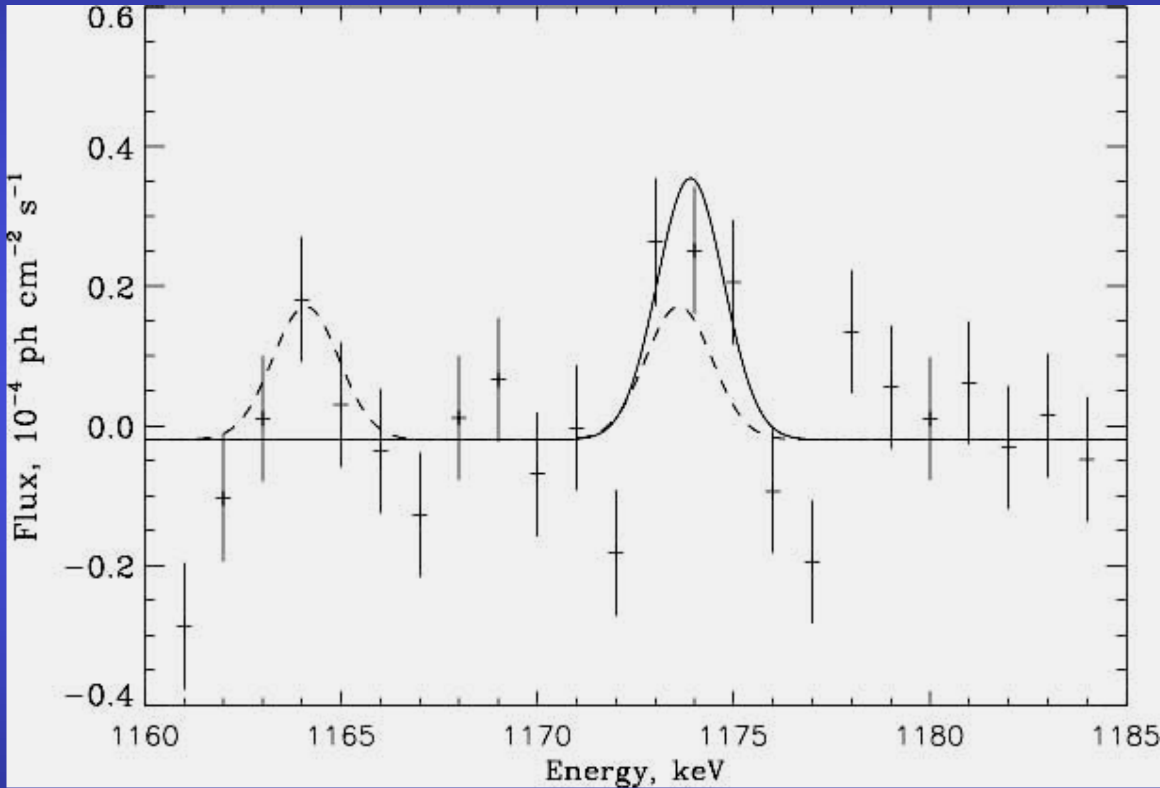




INTEGRAL

(Knödlseder et al. 2004)

^{60}Fe (1173 keV) in the galactic plane :
RHESSI detection confirmed by INTEGRAL



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

INTEGRAL
(Harris et al. 2005)

INTEGRAL γ-rays from SFRs…

- Interstellar ^{26}Al consistent (~ 2) with theoretical predictions for massive star yields
- Interstellar ^{60}Fe detected (RHESSI result, 2004, confirmed). Neutron-rich, unambiguous signature of « core-collapse SN » (observed as "SNII": $M_* > 8\ M_\Theta$).
- Observed ^{60}Fe/^{26}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) ?

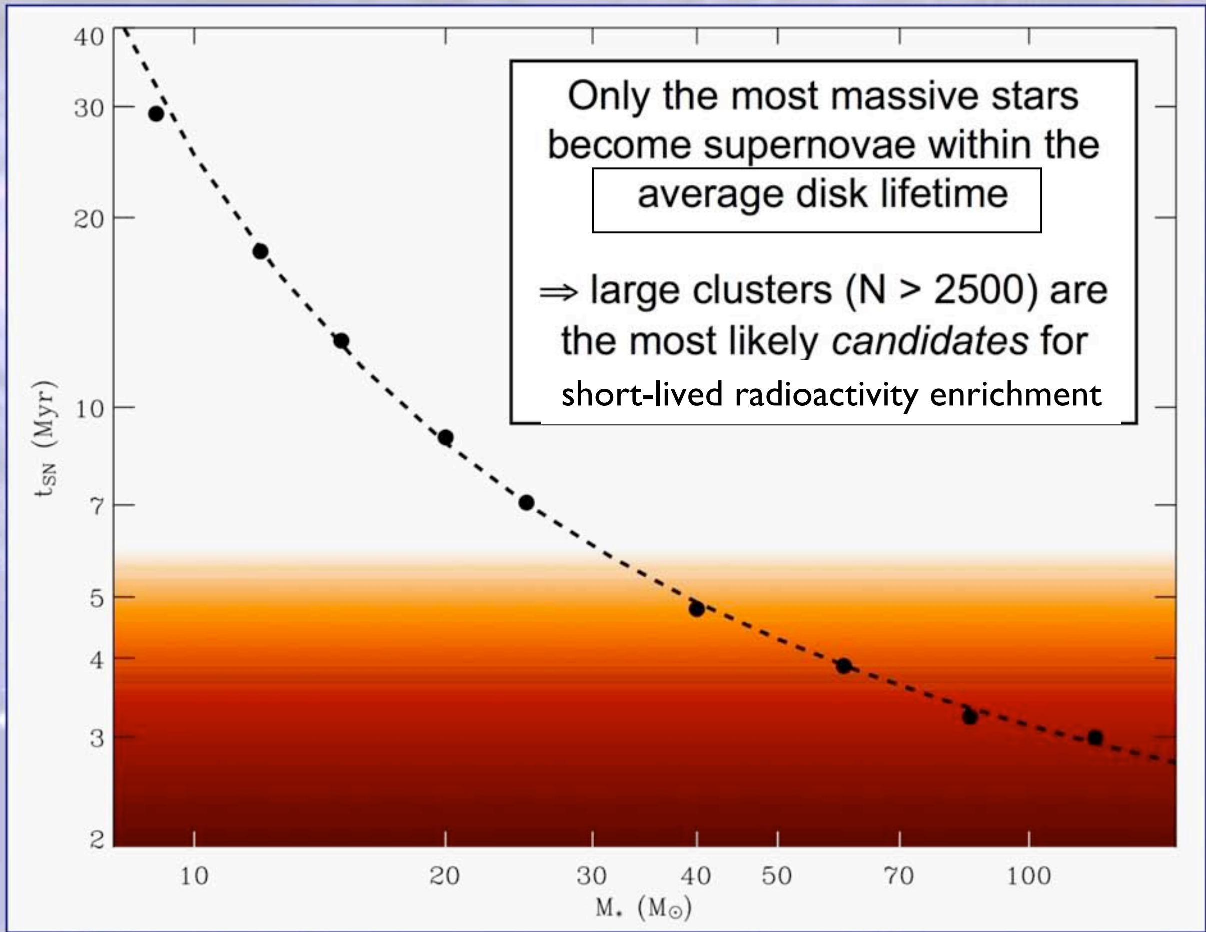
  More statistics needed (Harris et al. 2005, Knödelseder 2005)

  Nearby SFRs undetectable in ^{60}Fe - flux too low

- *Good agreement between theory and γ-ray observations confirm, in meteorites, the ^{60}Fe signature of a SN explosion within ~ 1 Myr of the formation of the Sun*

… is such an event probable ???

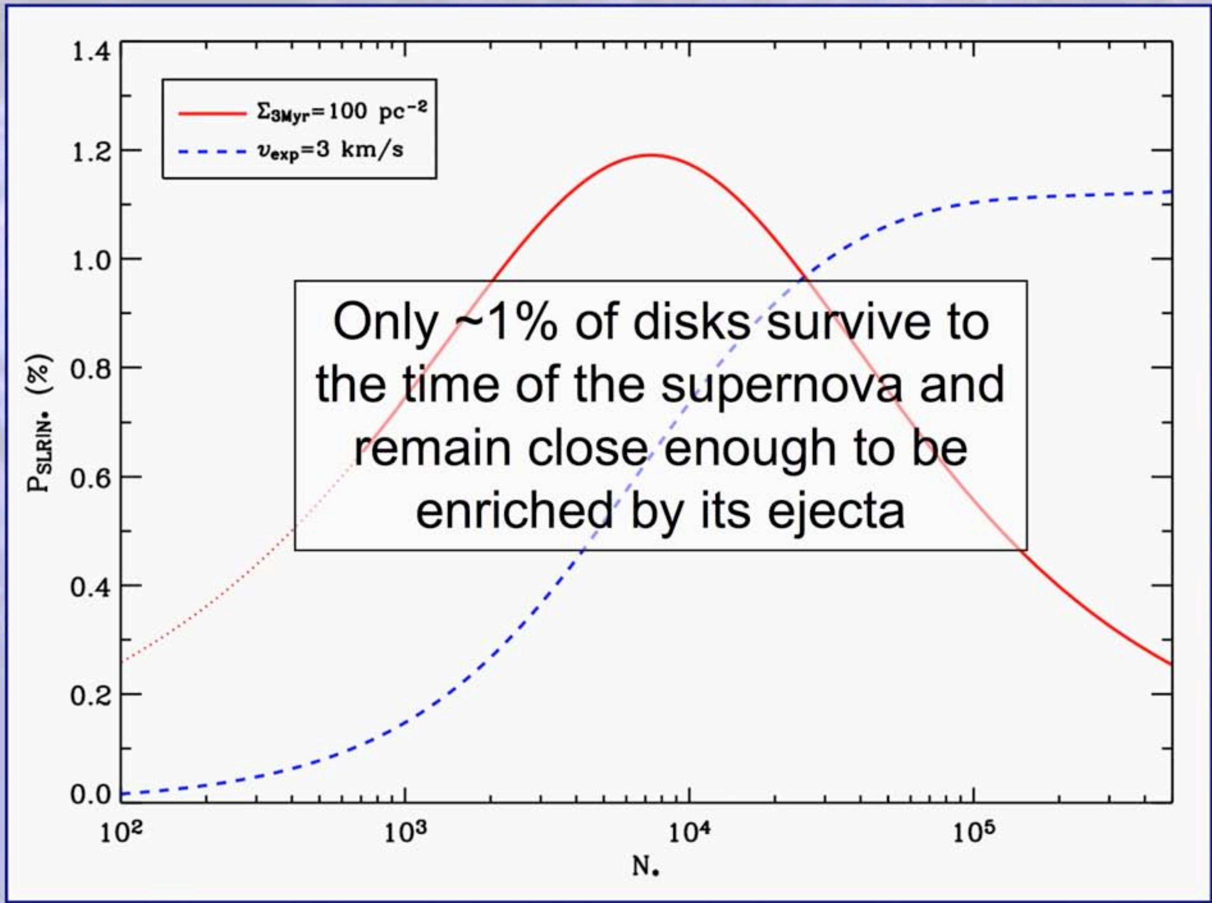
Supernova timescale vs disk lifetime



(Courtesy J. Williams)

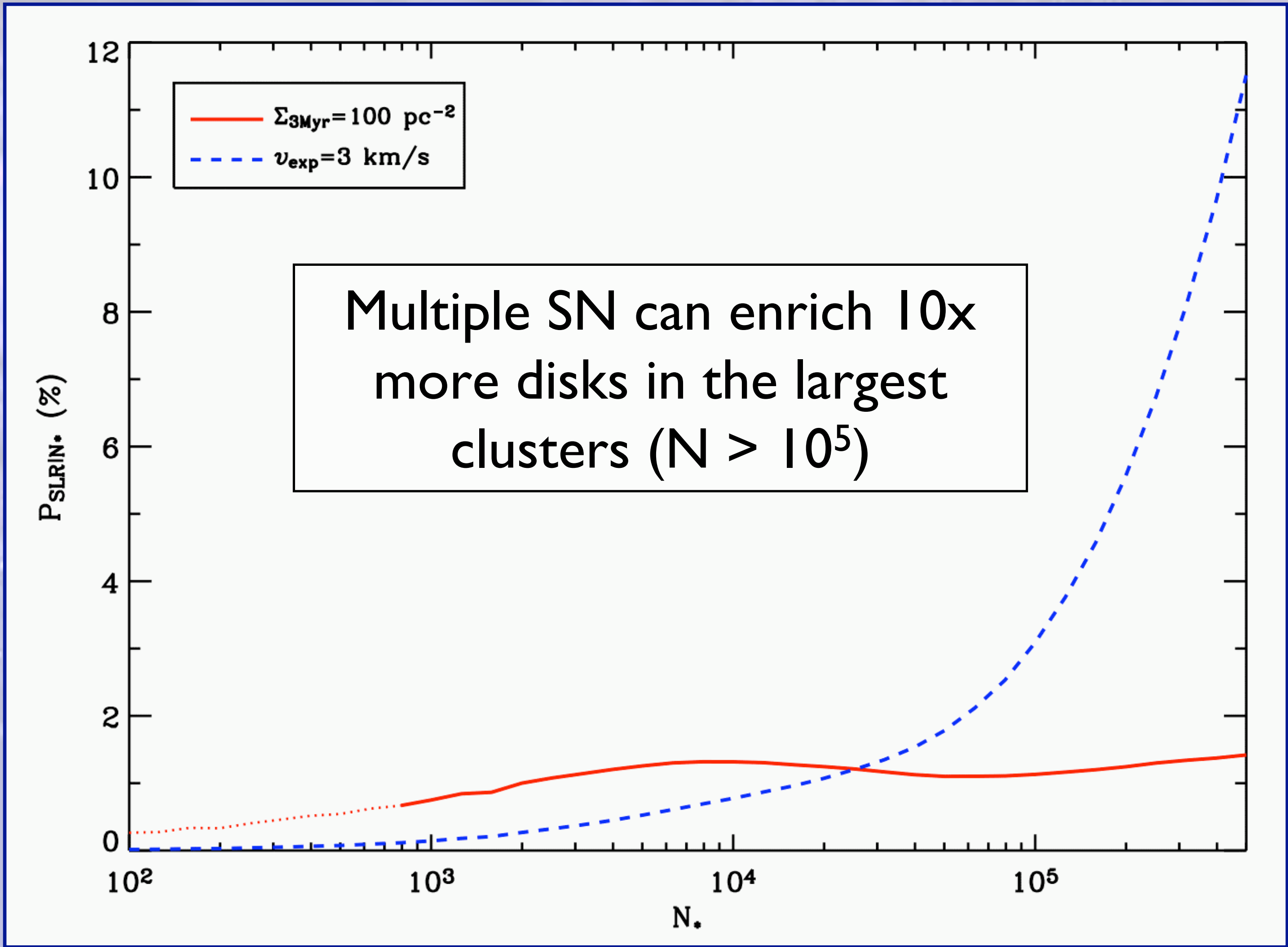
- ~70% of all stars form in clusters with N > 100 stars
- $dN_c/dM_c \sim M^{-2}$, $M_c = 10^2$-$10^6\ M_{sun}$
- 90% of clusters evaporate within ~10Myr
- the stellar density profile within a cluster is approximately inverse square (Adams et al. 2006; Lada & Lada 2003)

Enrichment fraction vs cluster size



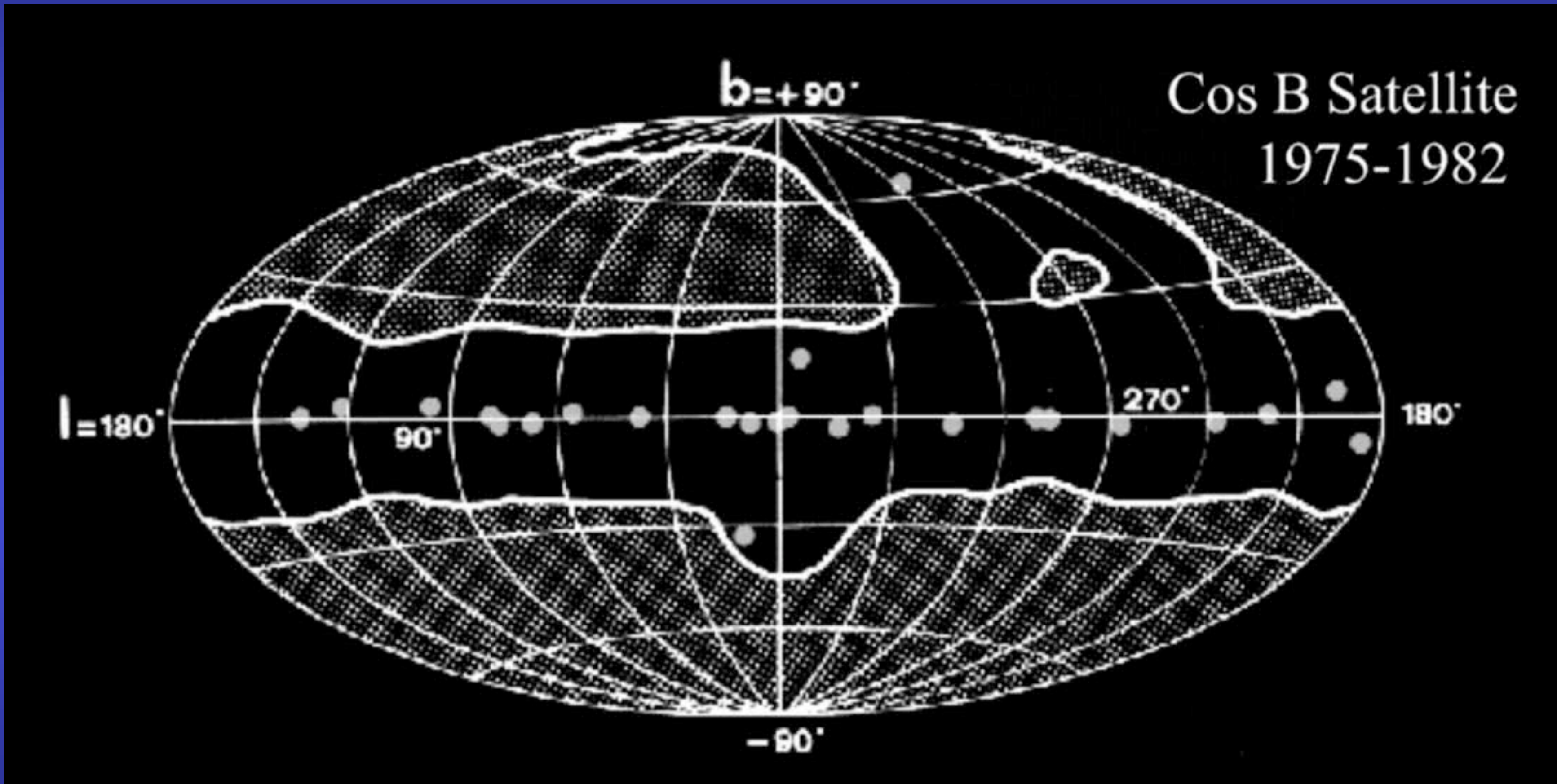
(Courtesy J. Williams)

Enrichment fraction vs cluster size (multiple supernovae)



(Courtesy J. Williams)

Une vieille histoire…



COS-B γ-ray sources (> 100 MeV) in the Galaxy (Torres et al. 2003)

THE ASTROPHYSICAL JOURNAL, **231**:95–110, 1979 July 1

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

THIERRY MONTMERLE
Section d'Astrophysique, Centre d'Etudes Nucléaires de Saclay, France
Received 1978 July 26; accepted 1979 January 5

ABSTRACT

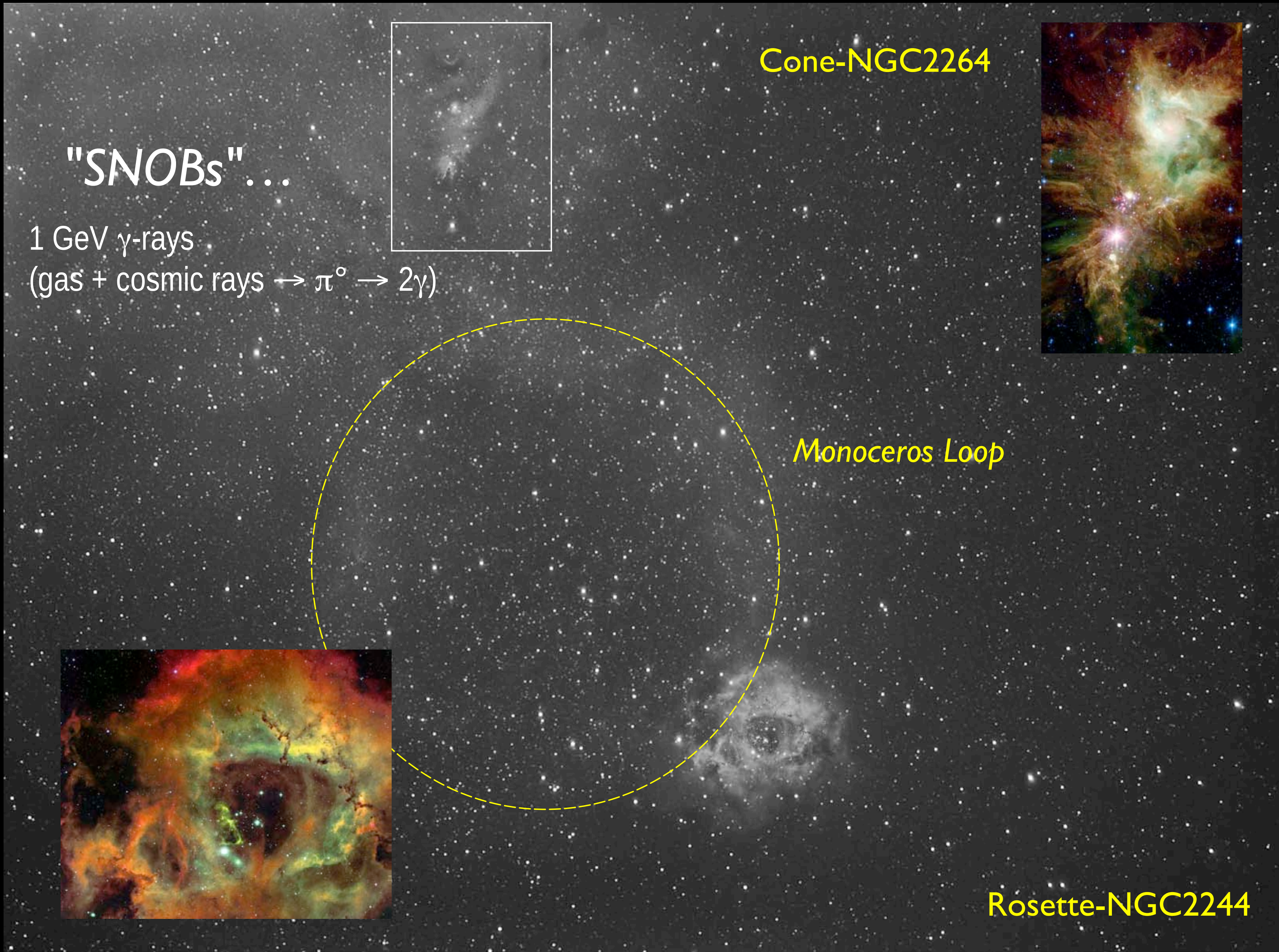
Although supernova explosions are widely thought to give rise to cosmic rays (nucleons), there is, as yet, no direct evidence from individual objects to support this view. A possible tool in this respect is the detection of γ-rays emitted by supernova remnants (SNRs) via π^0 decay, which results from 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 $\sim$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


"SNOBs"...
1 GeV γ-rays
(gas + cosmic rays → π° → 2γ)
Cone-NGC2264
Monoceros Loop
Rosette-NGC2244

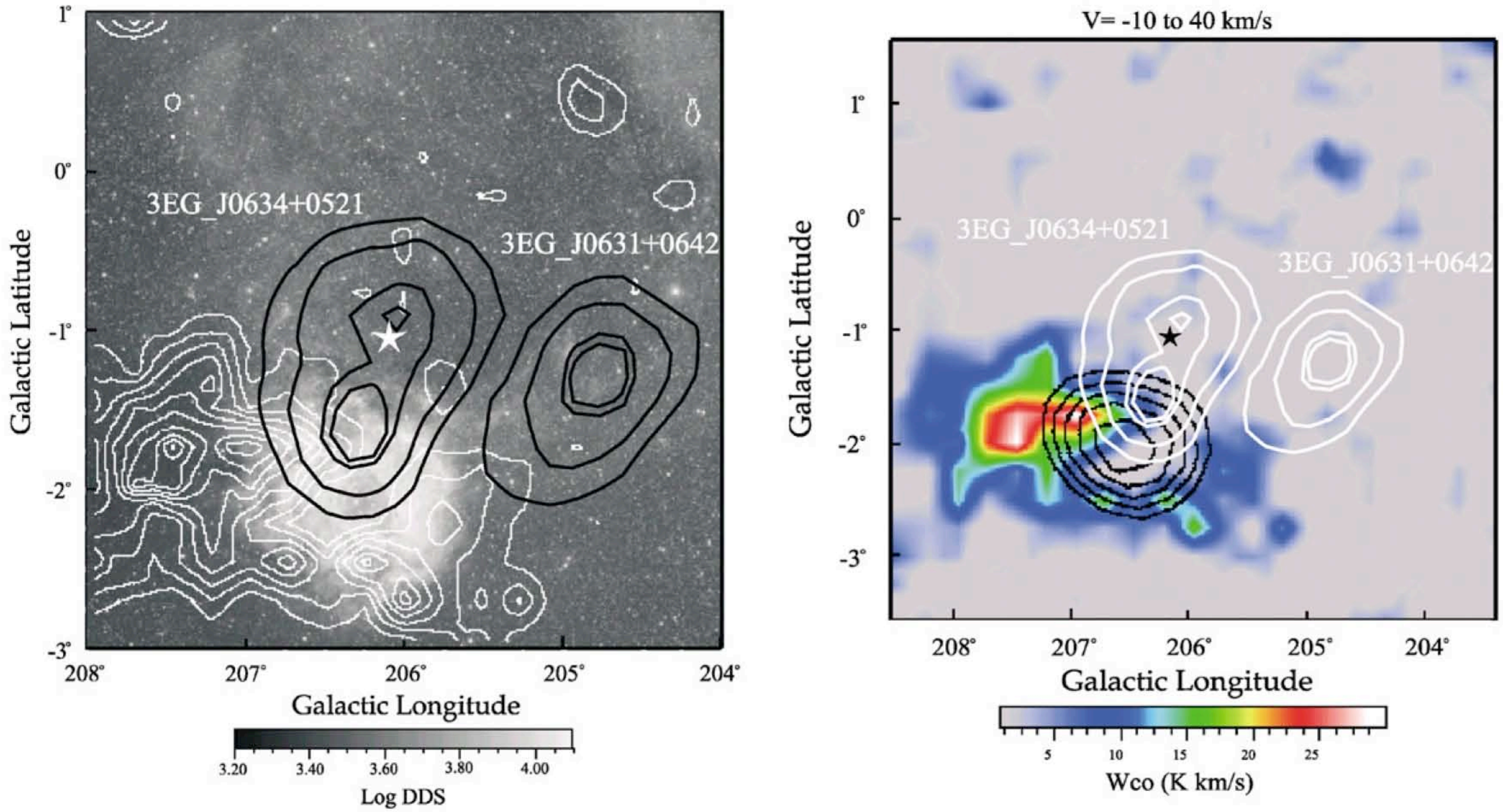
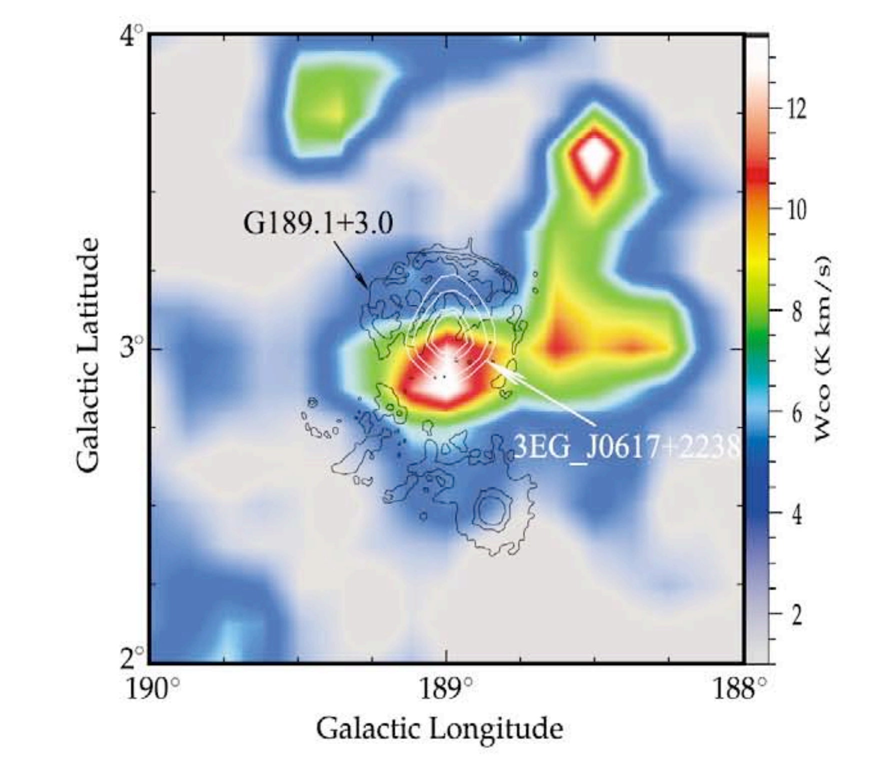
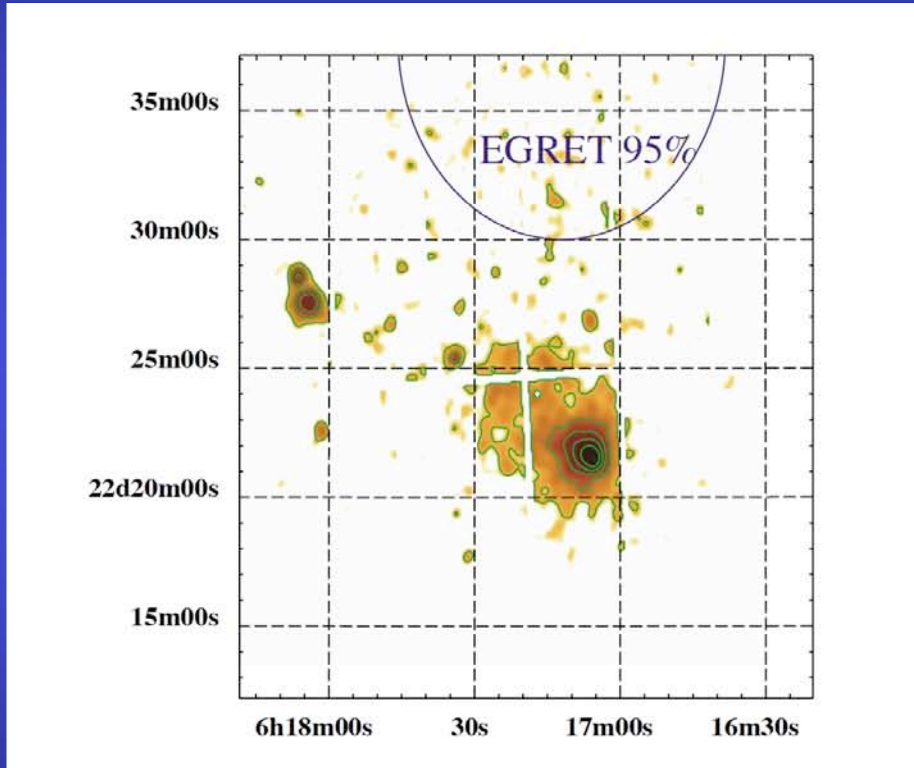


Fig. 12. Left: CO contours (white) on a background image from the Digital Sky Survey. The map covers a somewhat larger region than the left panel figure, and shows the HII region and young cluster NGC 2244 producing a hole in the cloud. Most of the Monoceros Loop is also seen faintly. EGRET sources contours are marked in black. Right: CO emission plus contours (black) of 1.4 GHz emission to mark the Rosette Nebula. The peak of the CO emission if near 3EG J0634 + 0521. The position of the X-ray source SAX J0635 + 0533 is marked with a star. White lines are the confidence levels of the EGRET sources.

IC443 SNR (optical)

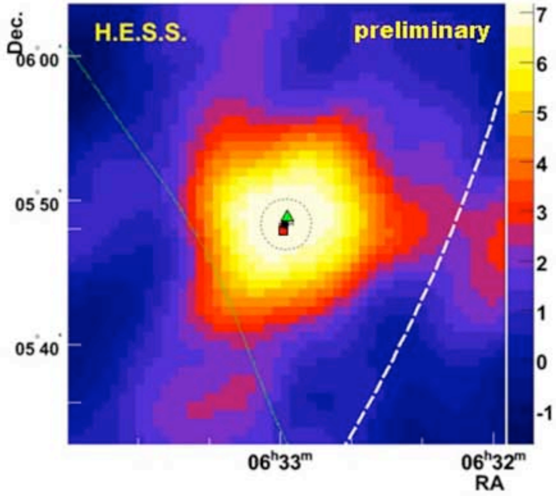
IC 443 (plerion): γ, CO, X>3 keV

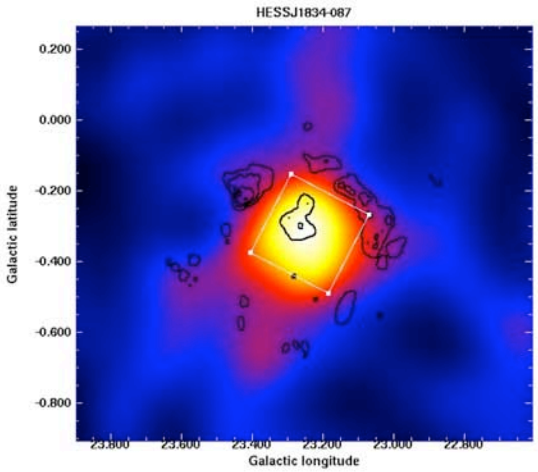


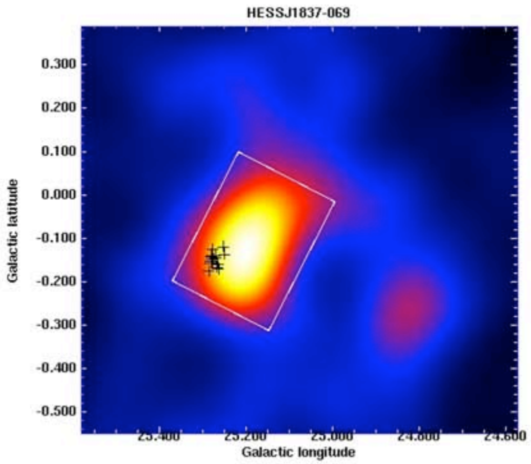


Better sensitivity (x 30) and angular resolution (≈ 1') in > GeV γ-rays ☞ GLAST (2008)

Sources HESS (>1 TeV) associées à des nuages moléculaires ?







The "dark accelerators"

4. Conclusions:
la formation du système solaire aujourd'hui
1. Des étoiles au Soleil

- Toutes les étoiles "nouvelles-nées" sont entourées de disques circumstellaires qui engendrent des jets bipolaires par *couplage magnétique* au voisinage de l'étoile centrale
- Dans les régions de formation d'étoiles massives (type Orion), les disques sont vaporisés en ~ 1 Myr par leur rayonnement UV => *conditions de survie des disques ?*
- La durée de vie des disques est de *quelques Myr*
  - <=> probablement lié à la formation des planètes géantes
- Les disques sont *fortement irradiés* par les éruptions X (donc par des noyaux énergétiques, *par analogie avec le Soleil*)
- Les archives météoritiques nous apprennent que:
  - Le Soleil est né il y a 4.567 Gyr
  - Le système solaire naissant a dû être sujet à une irradiation intense (~ x 10^4 aujourd'hui) par des particules énergétiques pendant ~ 10 Myr, en accord avec les observations X détoiles jeunes *(explique le ^{7}Be + peut-être tous les isotopes sauf ^{60}Fe)*

4. Conclusions:

la formation du système solaire aujourd'hui

2. Le berceau du Soleil

- D'après les statistiques, le Soleil a *a priori* une probabilité > 70% d'être né dans un "amas stellaire" (N > 100 étoiles)
- Ceci est confirmé par le fait que le système solaire jeune (< 1 Myr) a été contaminé par une supernova proche (^{60}Fe), quoiqu'avec une *très faible probabilité:* ~1% (1 SN) à 10% (multiple SN)
  - Contamination possible par ^{26}Al "ambiant" d'étoiles massives (vents)
- *=> le Soleil est vraisemblablement né dans une "association OB" très riche (~ 10^{4-5} étoiles), semblable à celles connues aujourd'hui sous le nom de "SNOBs", découvertes en 1979 grâce à leur émission γ à haute énergie, et qui constituent ≈ 10% des associations OB*
- Alternativement, le ^{60}Fe peut être du plutôt à une *supernova "extérieure"* (ex.: génération précédente)
- Test sur les isotopes de l'oxygène (Gounelle & Meibom 2007)