High-energy phenomena in massive star-forming regions: clues to localized acceleration of cosmic rays ?

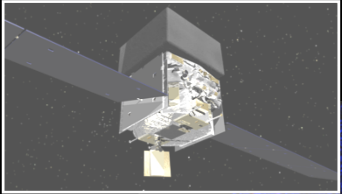
Thierry Montmerle
Institut d'Astrophysique de Paris, France

Outline

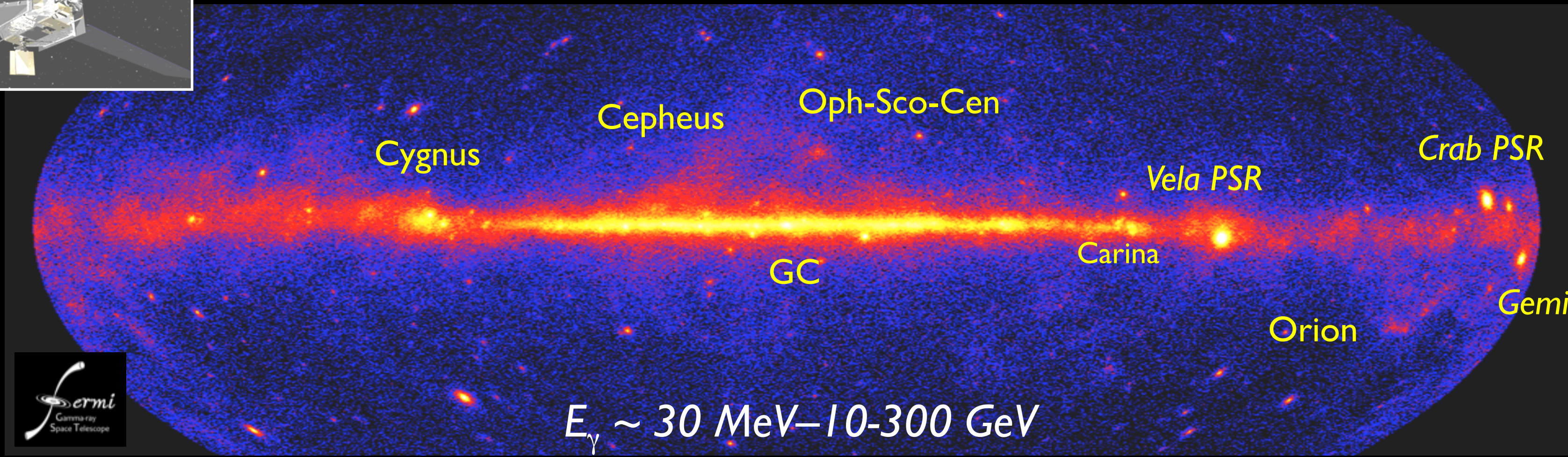
- 1. Introduction: main detection techniques, observations, and physical mechanisms
- 2. Massive star evolution and energetics in a nutshell
- 3. Feedback effects: hot plasmas in star-forming regions
- 4. SNR/molecular cloud collisions
- Concluding remarks

1. Astrophysical background

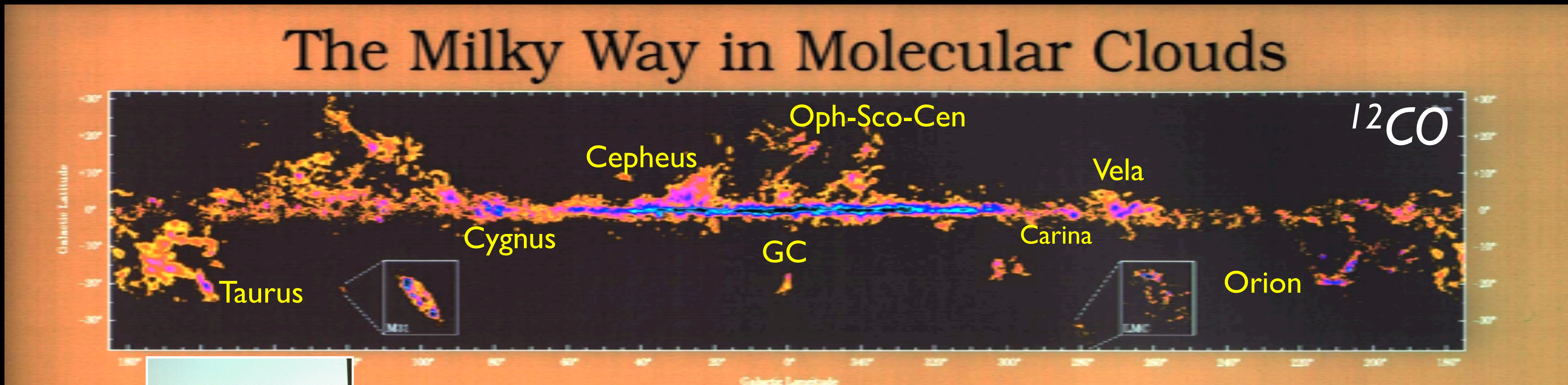
- Cosmic rays (CR: p, α, e^-) pervade the Galaxy. They are thought to be accelerated by supernova shocks ("supernova remants": SNR)
- They are traced by high-energy γ-rays (> GeV) when they interact with the interstellar medium (ISM: matter + ambient photons)
  - π° decay (p, α + H, He)
  - Inverse Compton (e^- + $h\nu$)
  - Bremsstrahlung (e^- + Z)
  - Synchrotron (e^- + B)
- => A γ-ray "source" *may* be associated with a localized CR source (e.g., a SNR), *once the galactic background has been properly removed,* with other consequences (ionization of molecular clouds, contamination by radioactive products….)
  - => possible clues to the origin of the solar system (*extinct radioactivities* in meteorites: ^{26}Al, ^{60}Fe, which decay by observable ~ MeV γ-ray line emission)

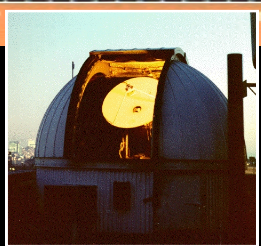


Galactic scale: p(CR) + p(ISM) —> π° —> 2γ



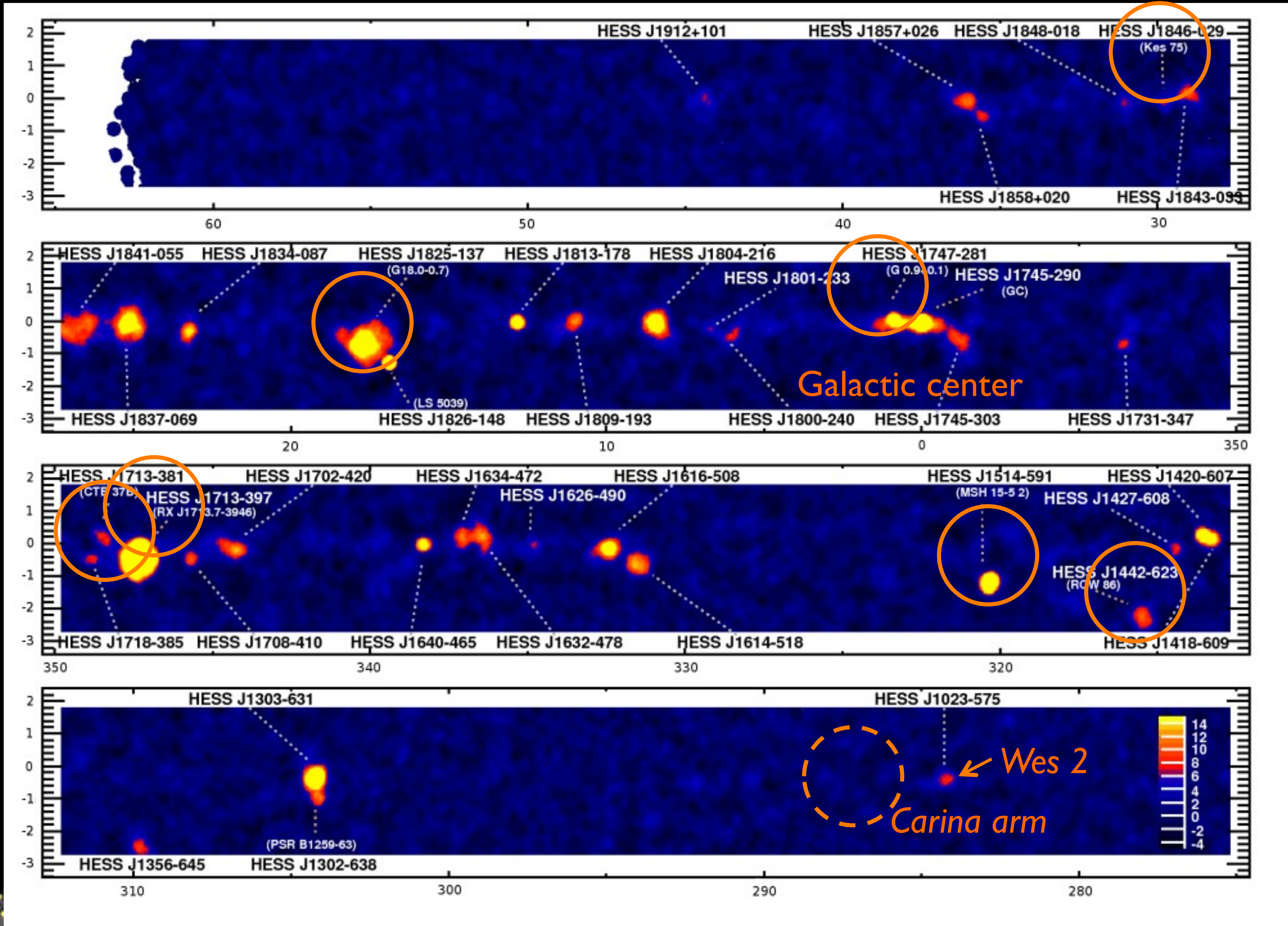
2^{nd} Fermi catalog (2009)





Dame et al. 2002

HESS galactic plane survey (TeV γ-rays)



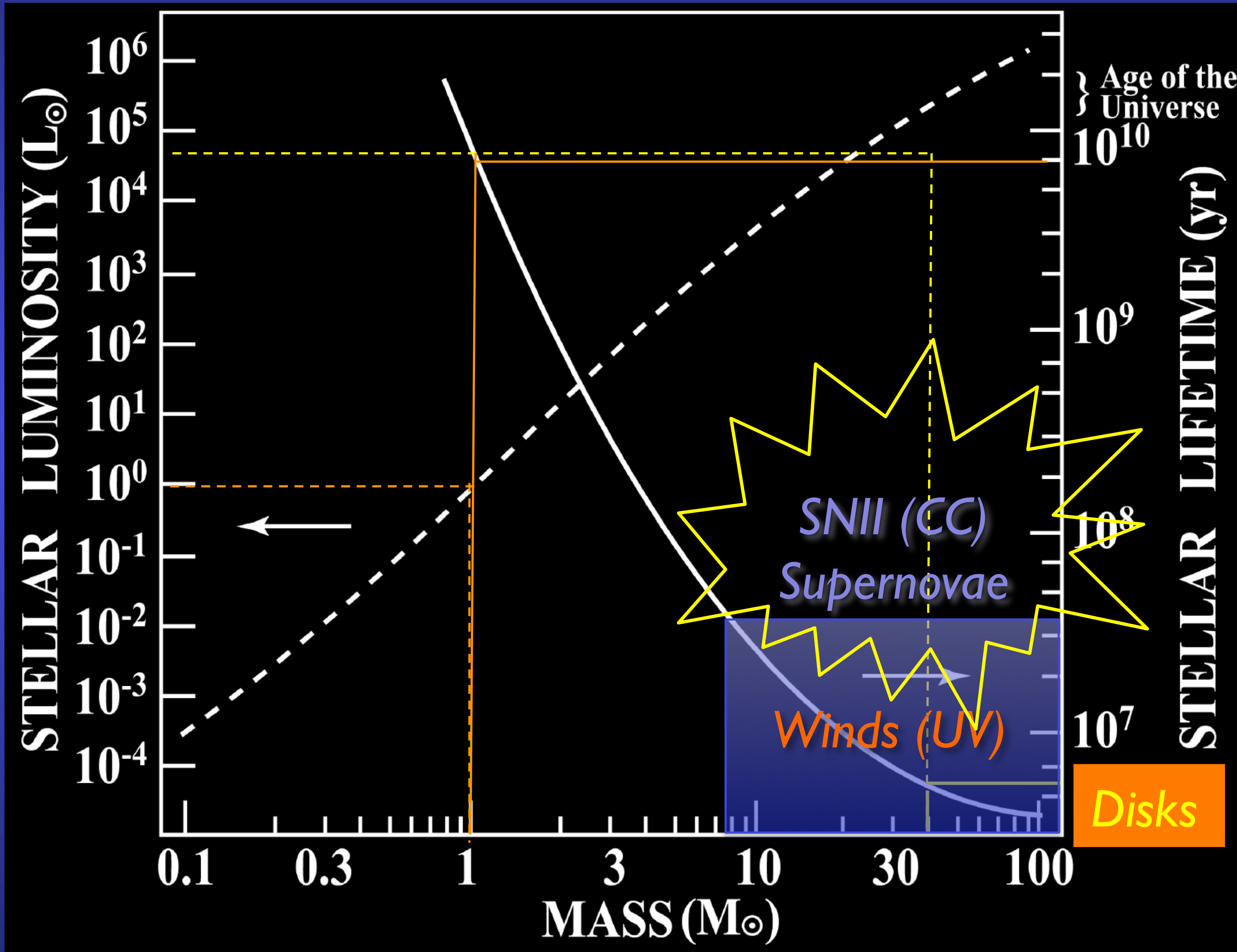
TeV γ-ray sources

- $\Delta\theta \sim 0.1° \sim$ mol. cloud @ 2-3 kpc
  - Strong concentration along the galactic plane
- So far, only a few cross-identifications between GeV (Fermi) and TeV sources
- Majority of identified sources connected with the end stages of massive star evolution:
  - A few compact X-ray binaries (accreting neutron star + companion)
  - Many "pulsar wind nebulae" (γ-rays from leptons: IC + synchrotron)
  - Isolated *young* supernova remants (synchrotron + IC)
  - Increasing number of *middle-aged* supernova remnants (SNRs; ~ x10^4 yrs) interacting with molecular clouds (*extended* γ-ray sources: CR hadrons at last ? (See COS-B GeV results: "SNOBs", Montmerle 1979 + others: CR x10-100)
- Still many unidentified sources ("dark accelerators")

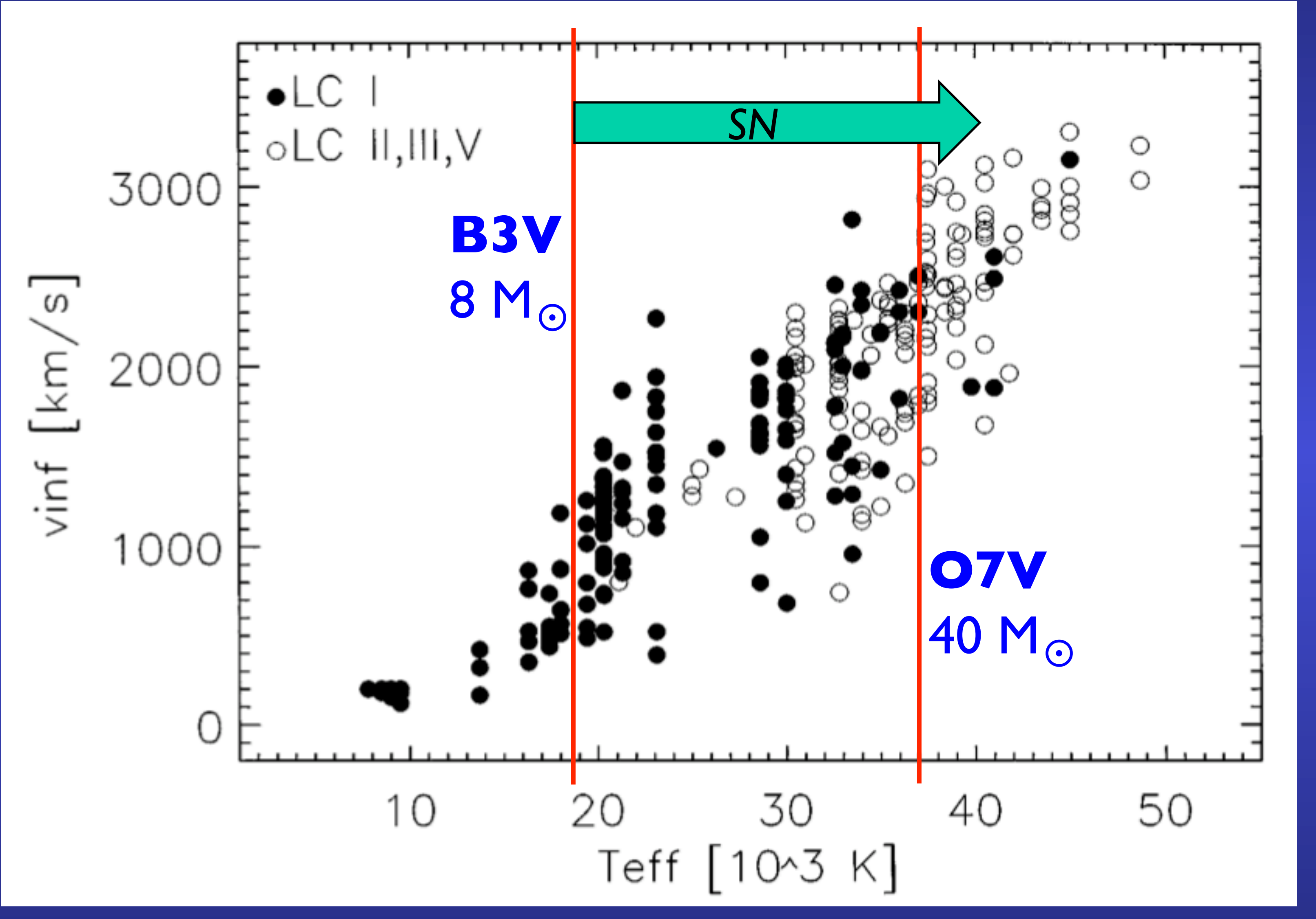
2. Massive star evolution

…for dummies ?

Stellar and disk lifetimes vs. winds & supernovae

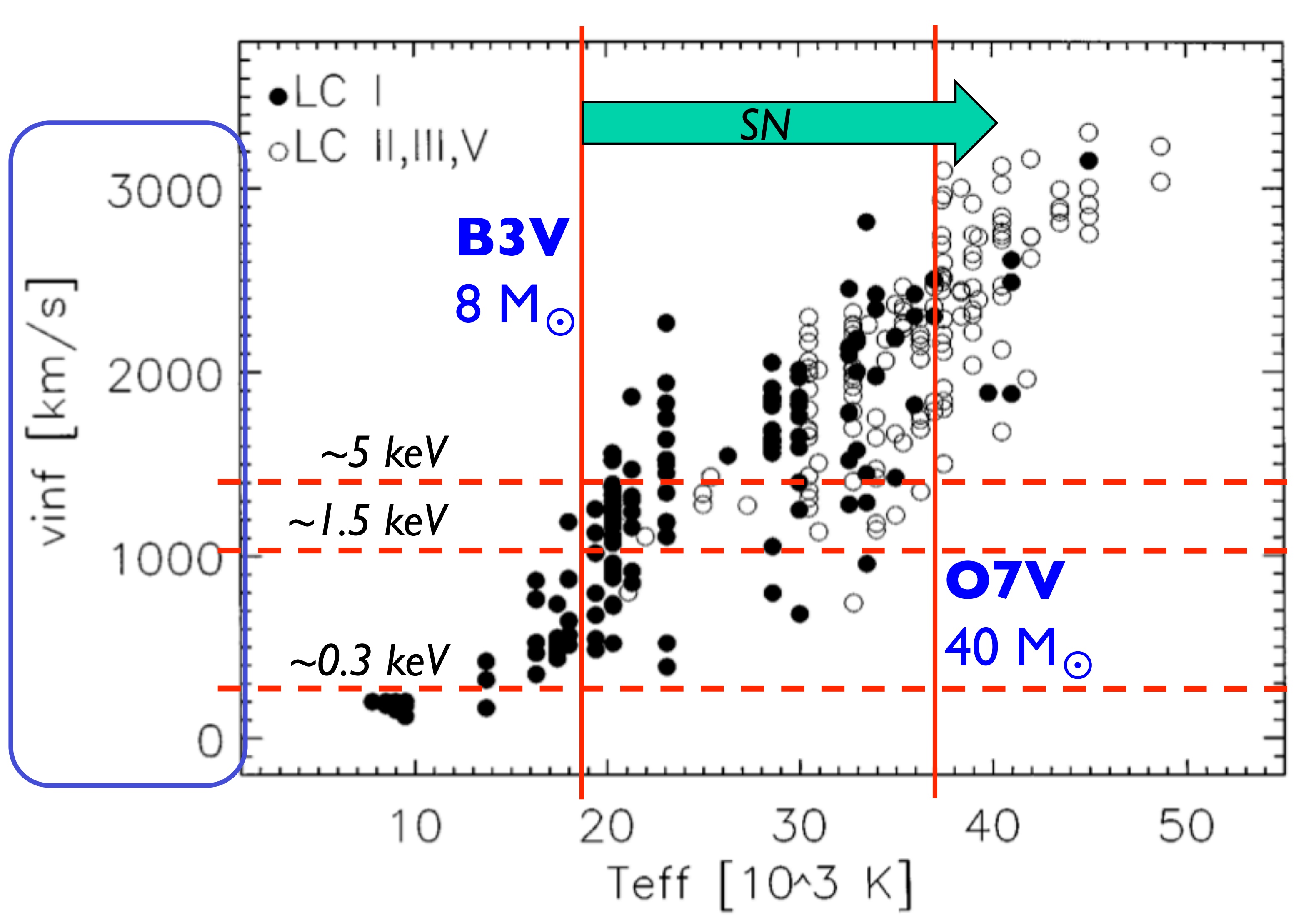


OB stars: Wind terminal velocity



Kudritzki & Puls 2000

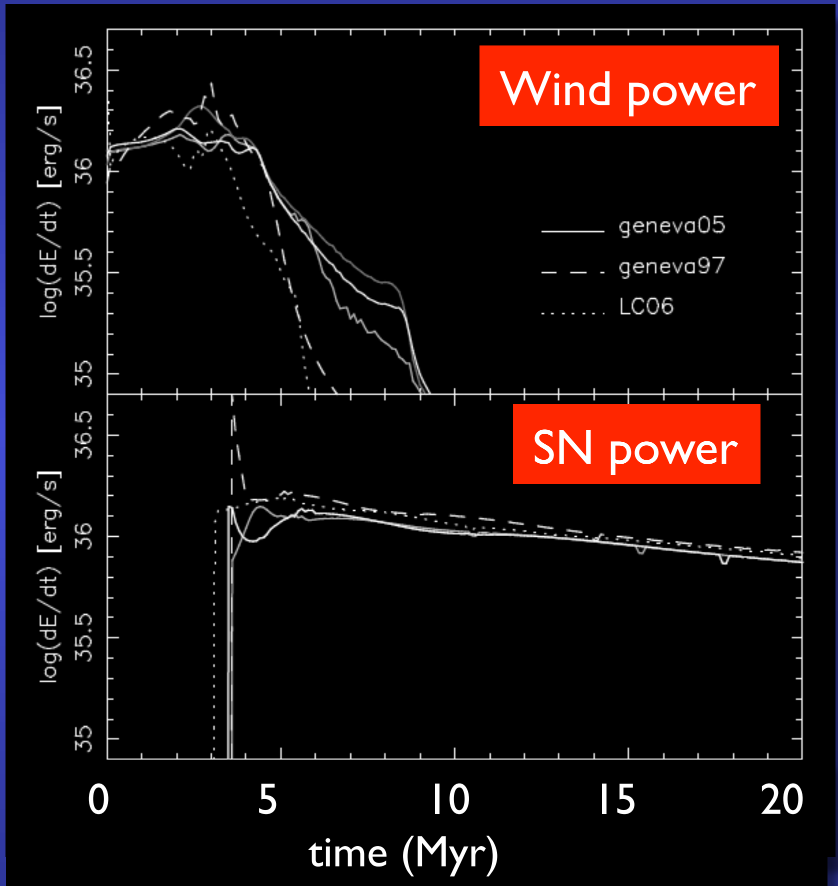
OB stars: Wind terminal velocity

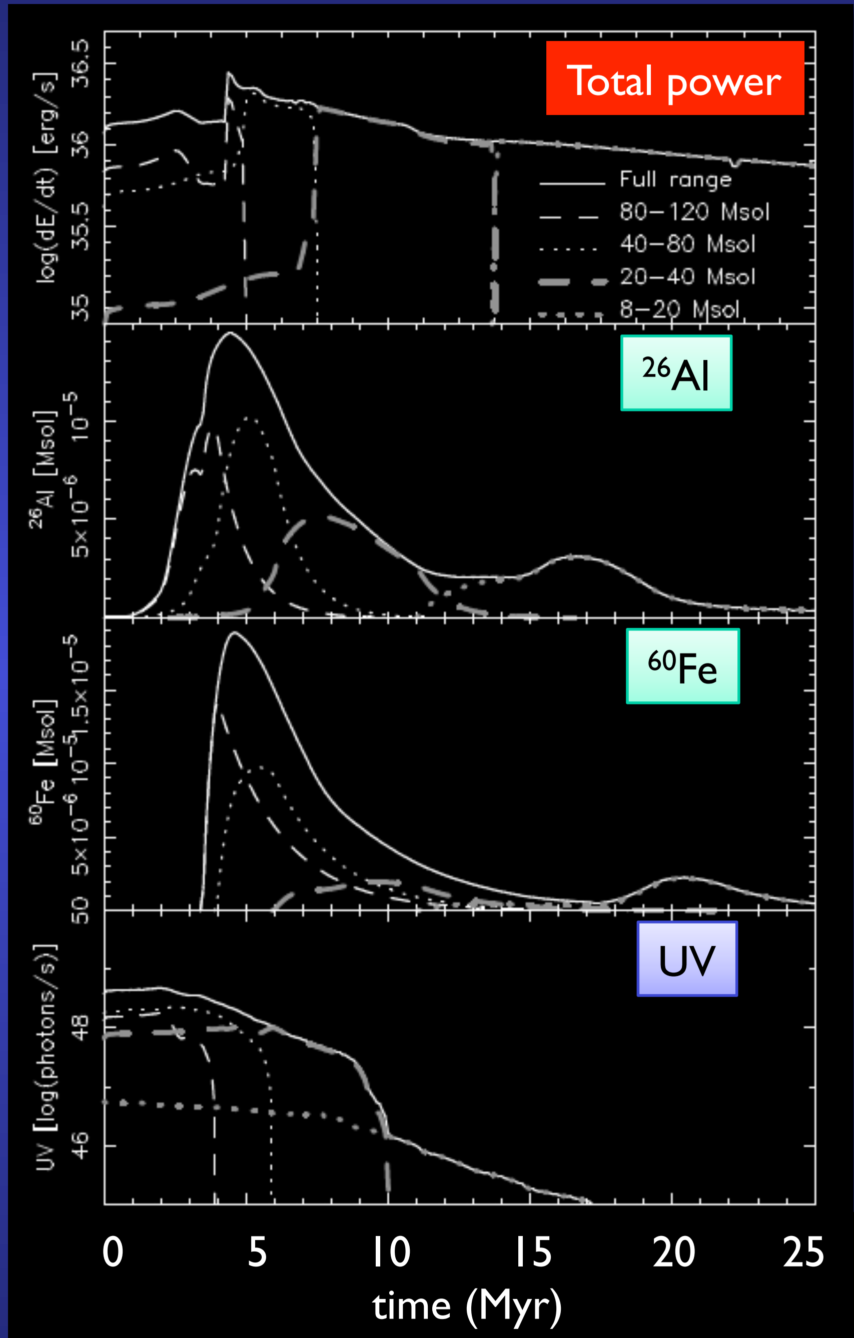


Kudritzki & Puls 2000

Massive stars:

output of a 8-120 $M_\odot$ OB association



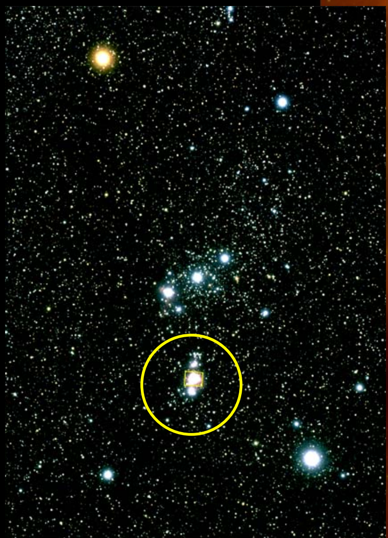


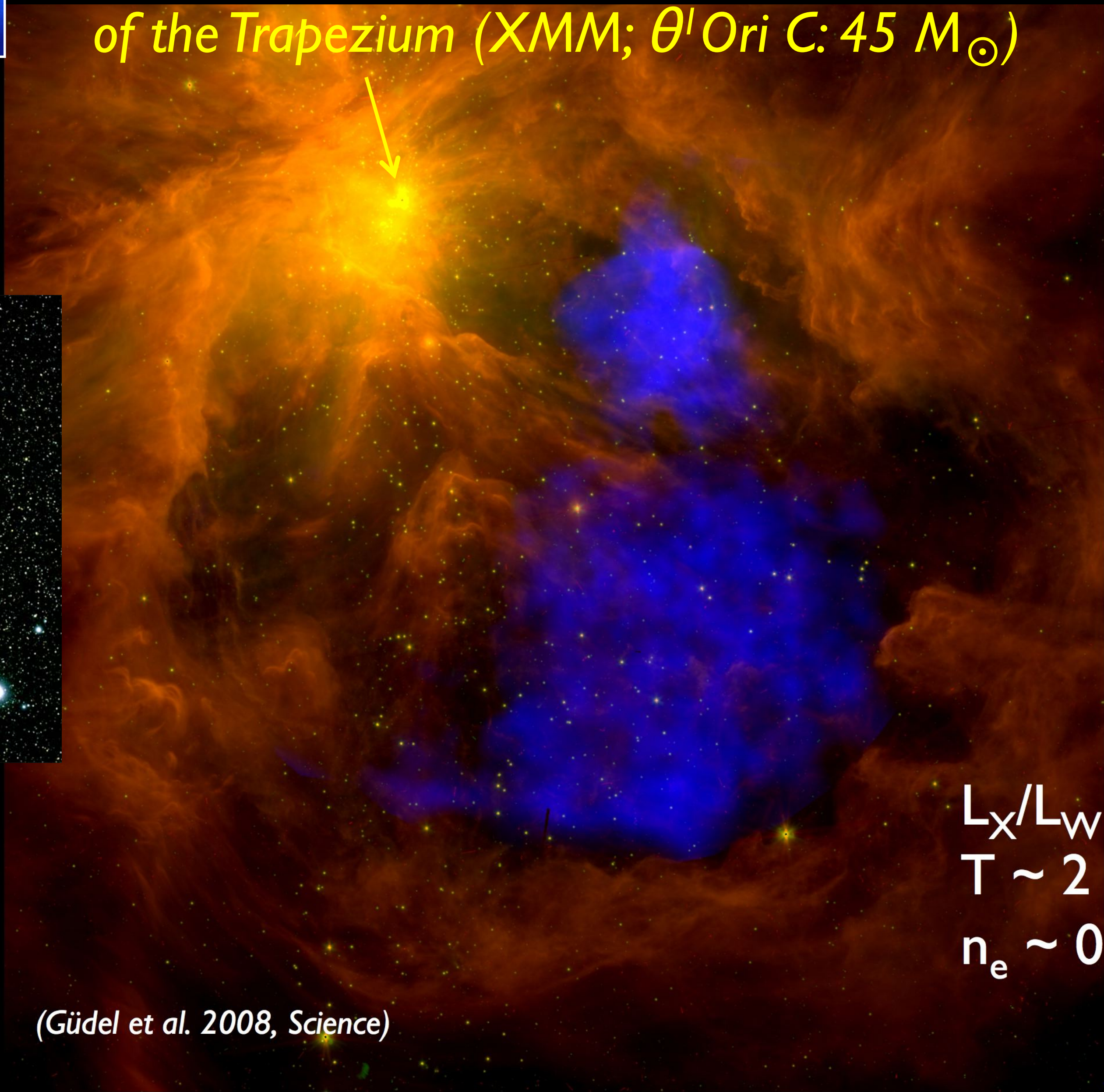
(Voss et al. 2009)

3. Feedback: Hot plasma bubbles

Orion: X-rays from shocked stellar winds of the Trapezium (XMM; θ^1 Ori C: 45 $M_\odot$)

XMM





(Güdel et al. 2008, Science)

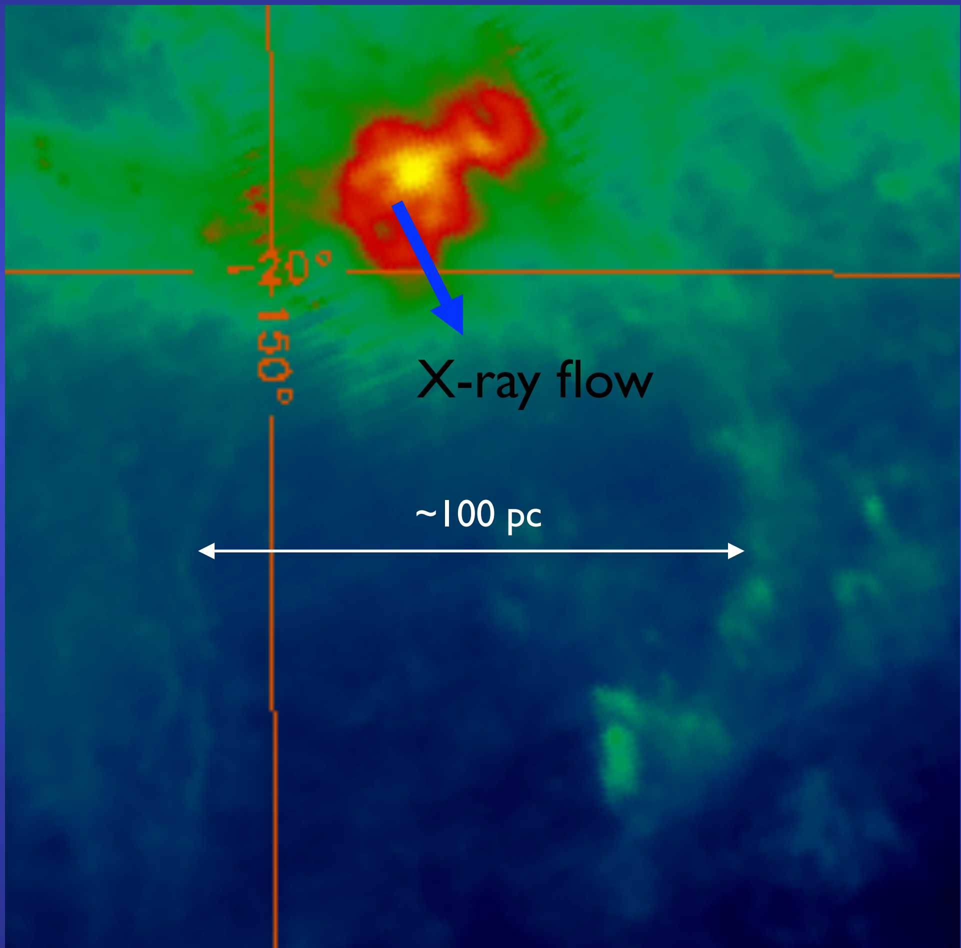
$L_X/L_W \sim 10^{-4}$

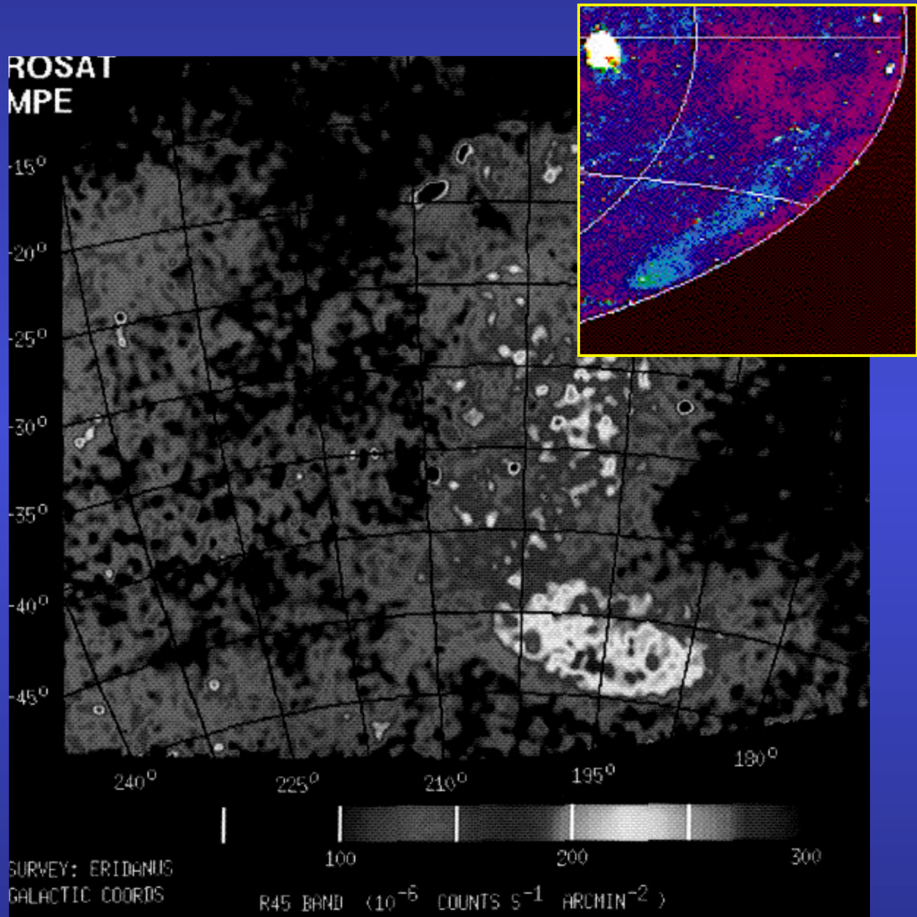
$T \sim 2$ MK

$n_e \sim 0.6$ cm^{-3}

plasma confined by cavity (pressure equilibrium); *cooling* ~ *Myrs*

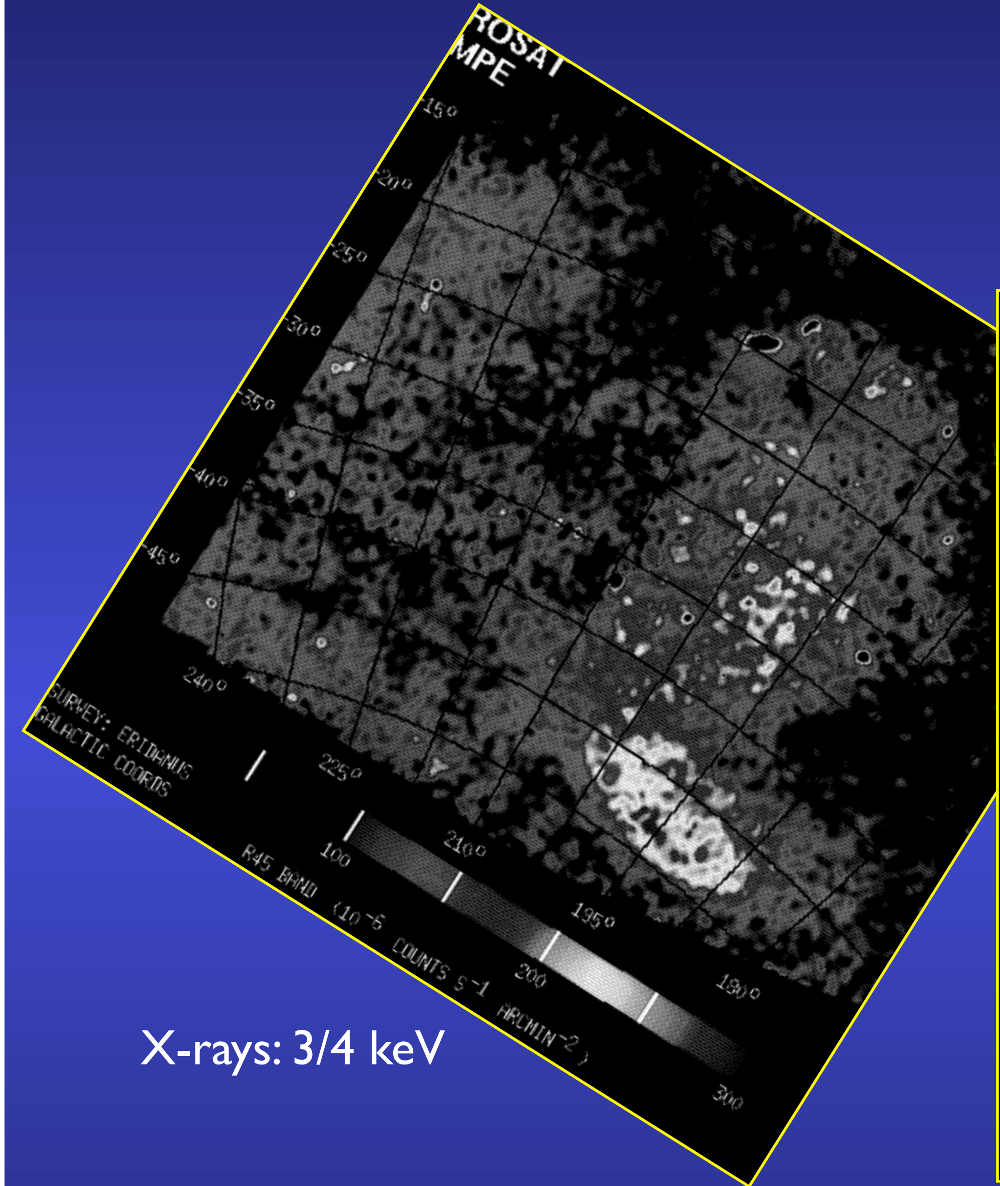
The "Eridanus superbubble": far, far away from the galactic plane…



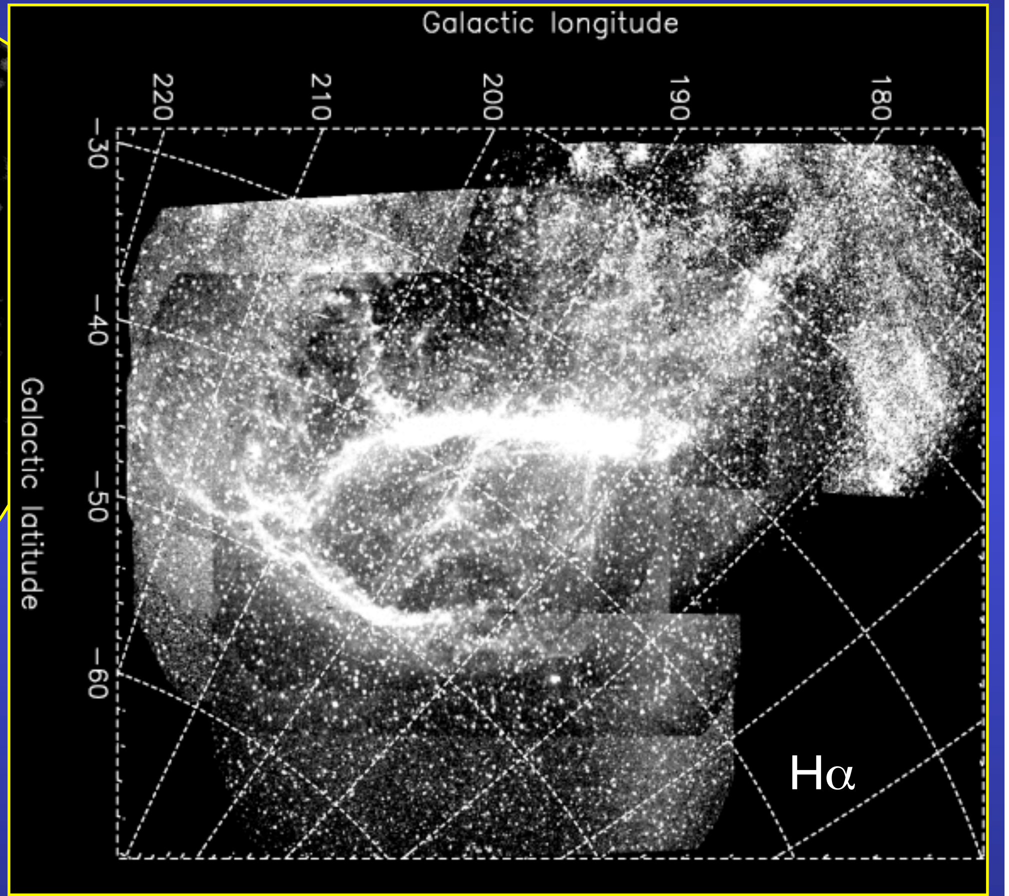


X-rays: 3/4 keV (Snowden et al. 1995)

The Eridanus Superbubble

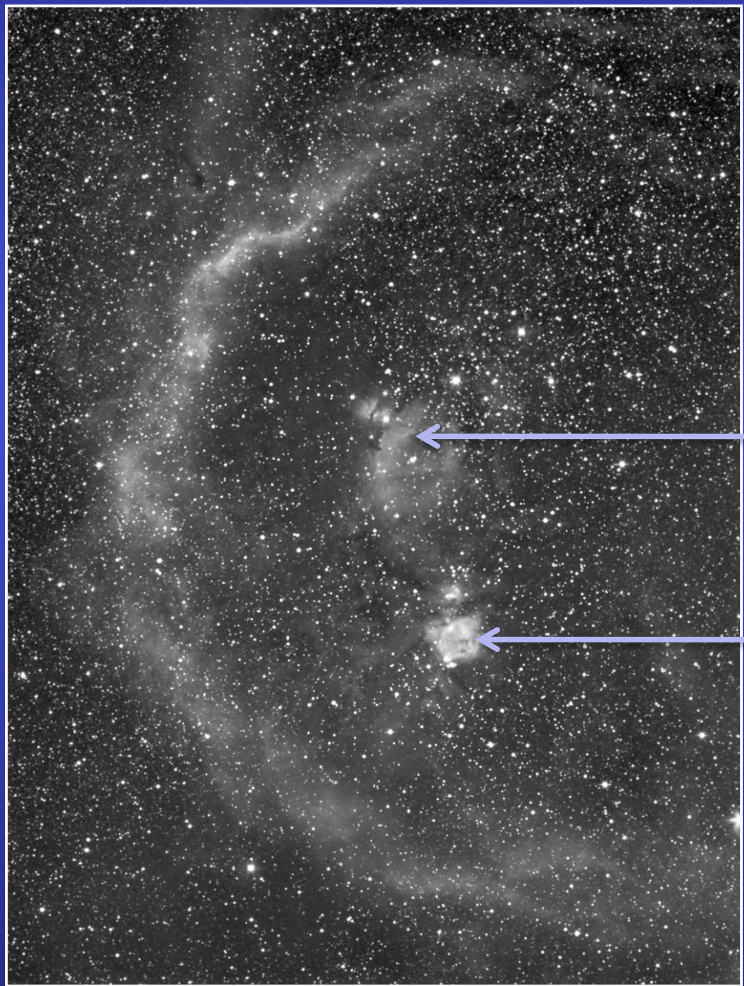


X-rays: 3/4 keV

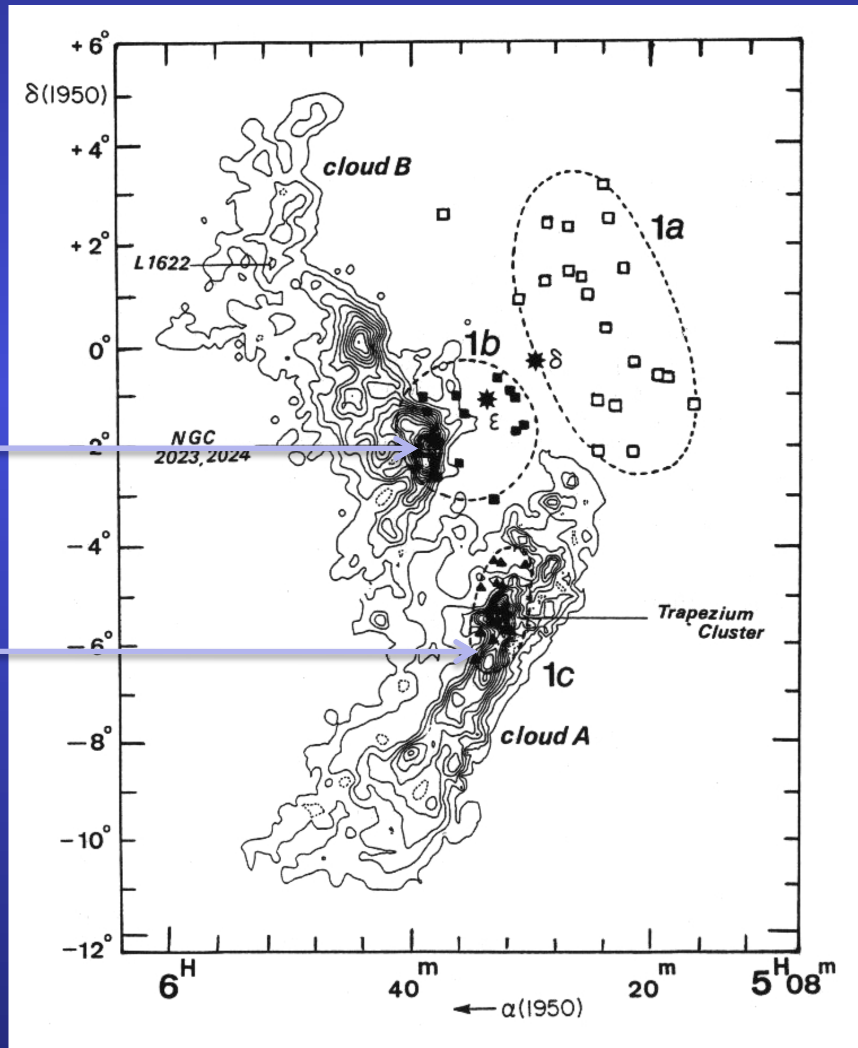


Successive generation of stars: “propagating star formation”

“Barnard’s Loop”: past SN (≈ 10)



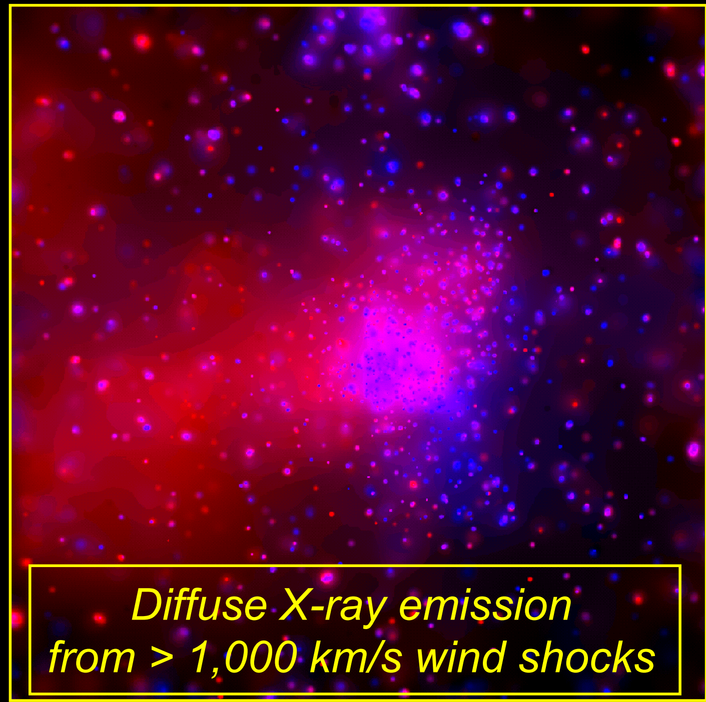
Orion OB associations: 1-15 Myr



M17, the Omega Nebula : a "hollow", hot HII region

2MASS (near-IR: 2 μm)

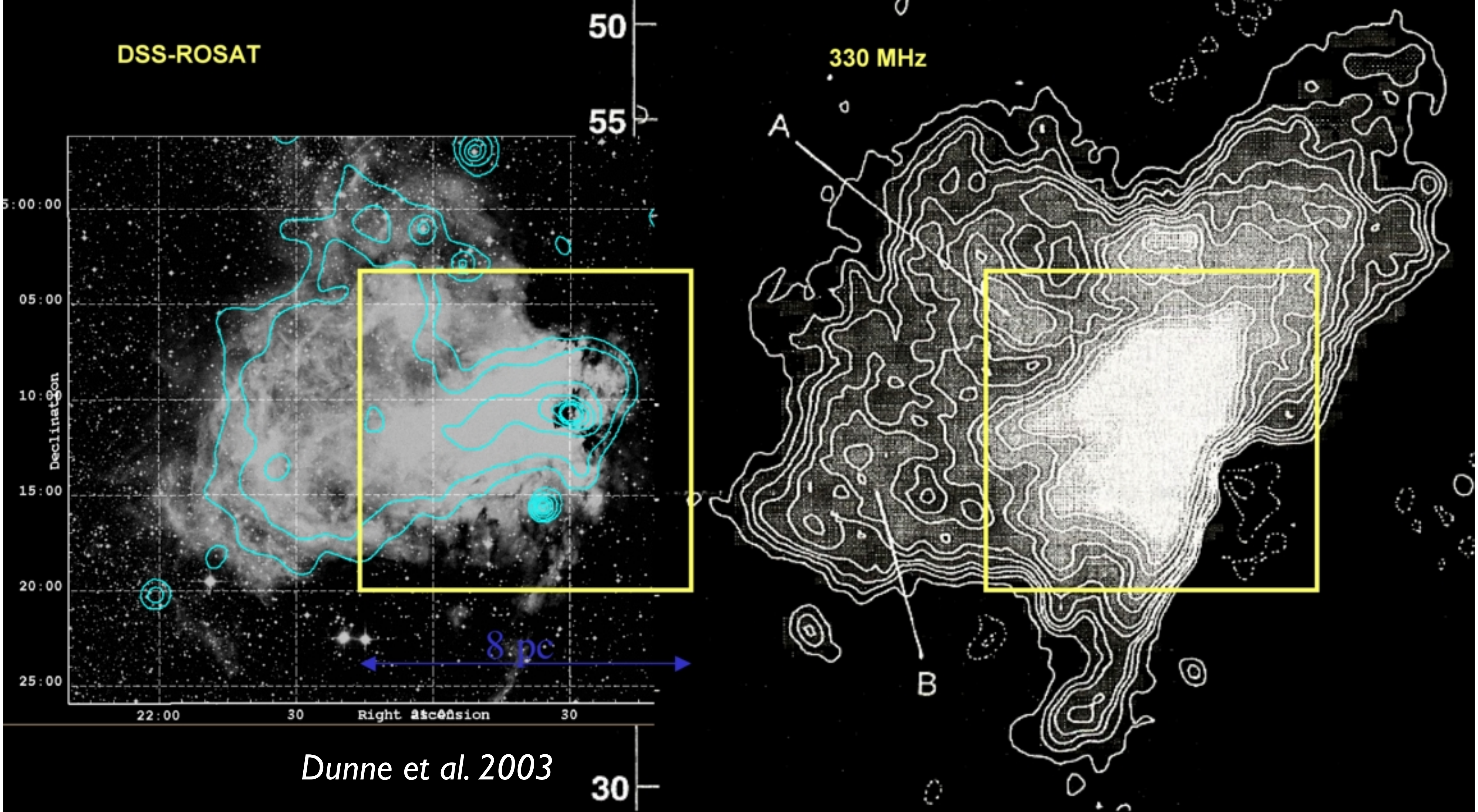
Chandra (X-rays: 0.5-10 keV; 10^6-10^7 K)



d ~ 2 kpc, ≥ 13 O (O3–>O9.5) + 34 B + x 1000 T Tauri stars

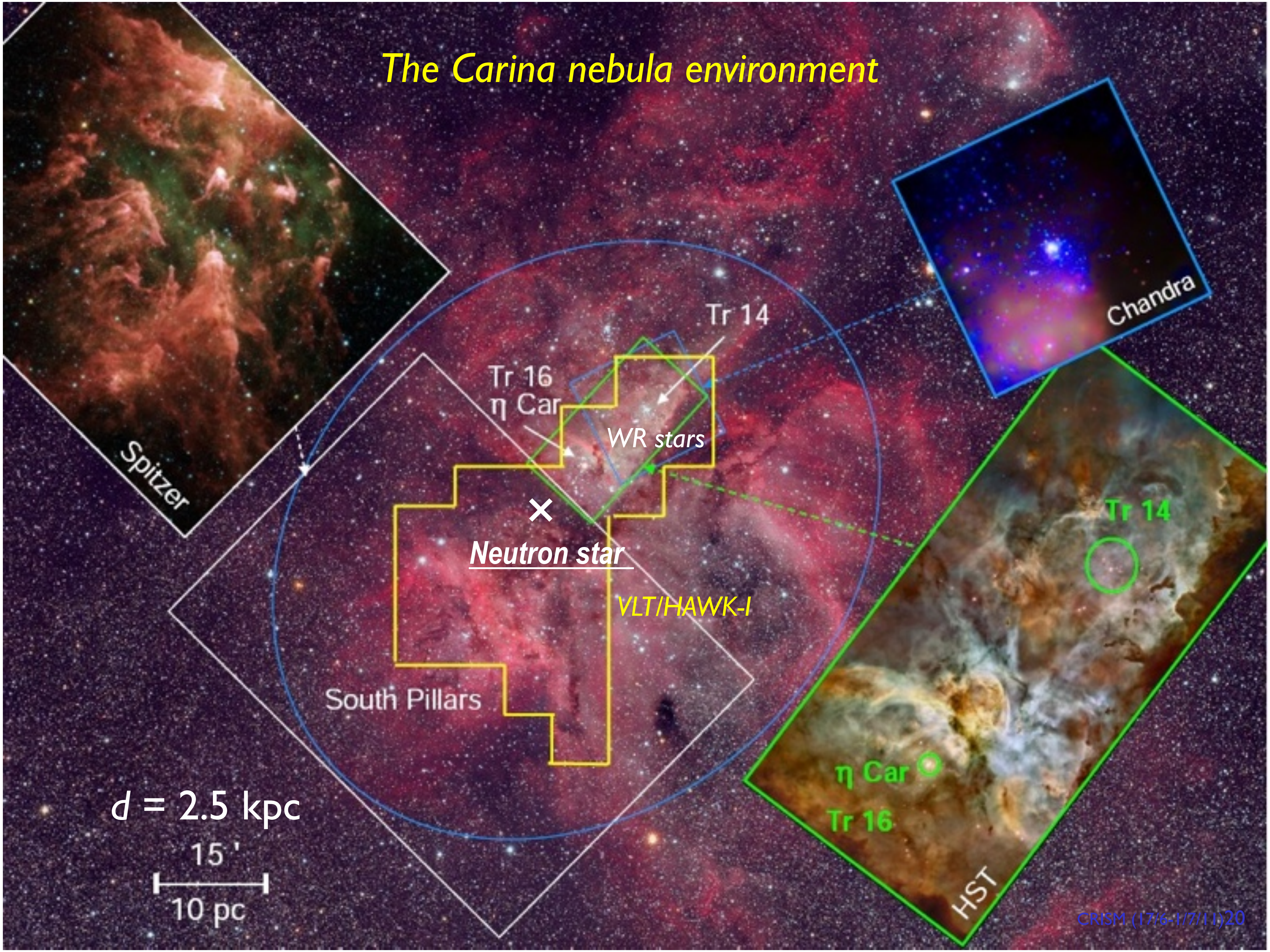
(Chandra: *Townsley, Montmerle, et al. 2003, ApJ)* (wind-shocked) plasma (⇔ X-rays) flow into the ISM…

~ *pressure equilibrium with cold ambient material*

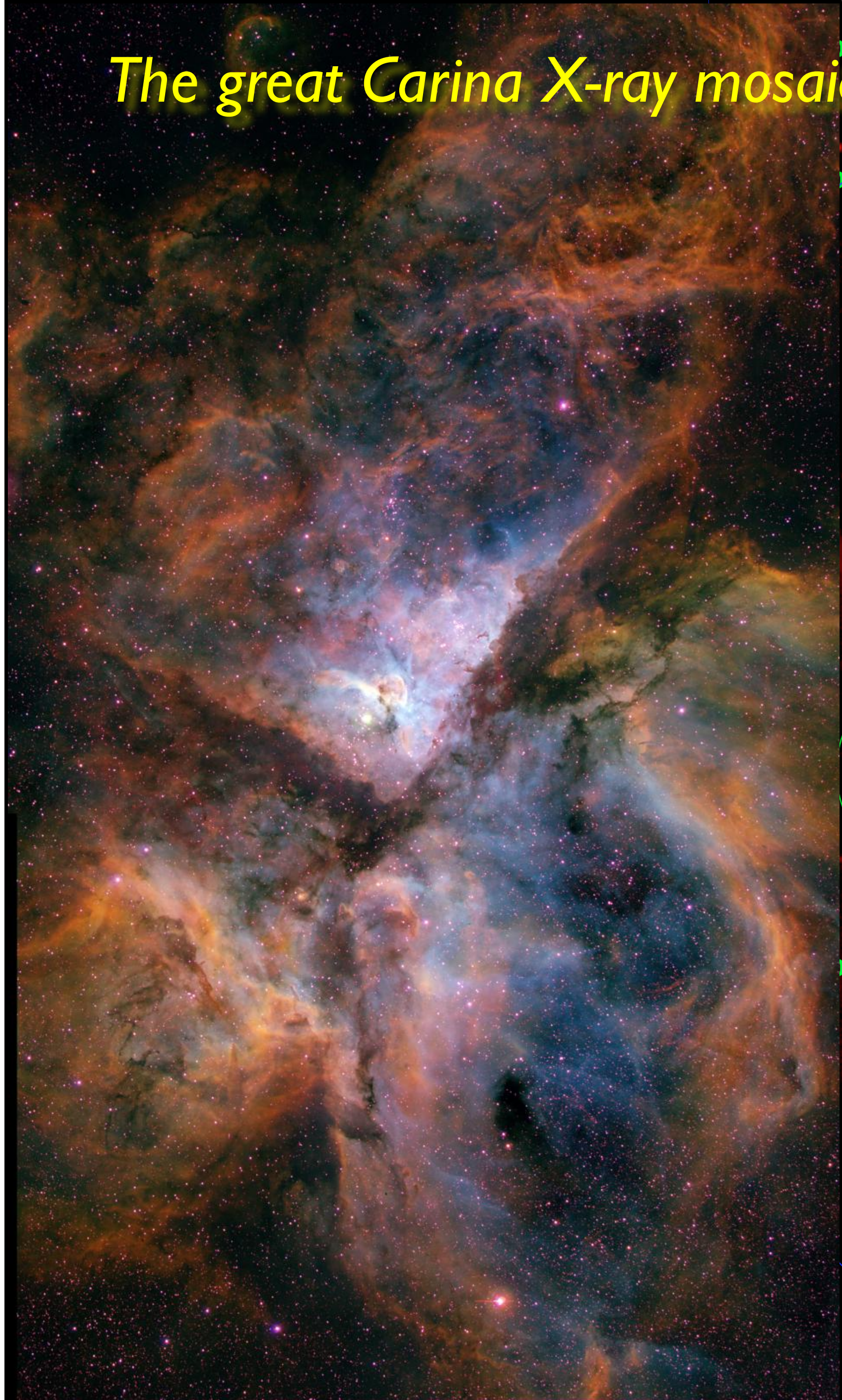


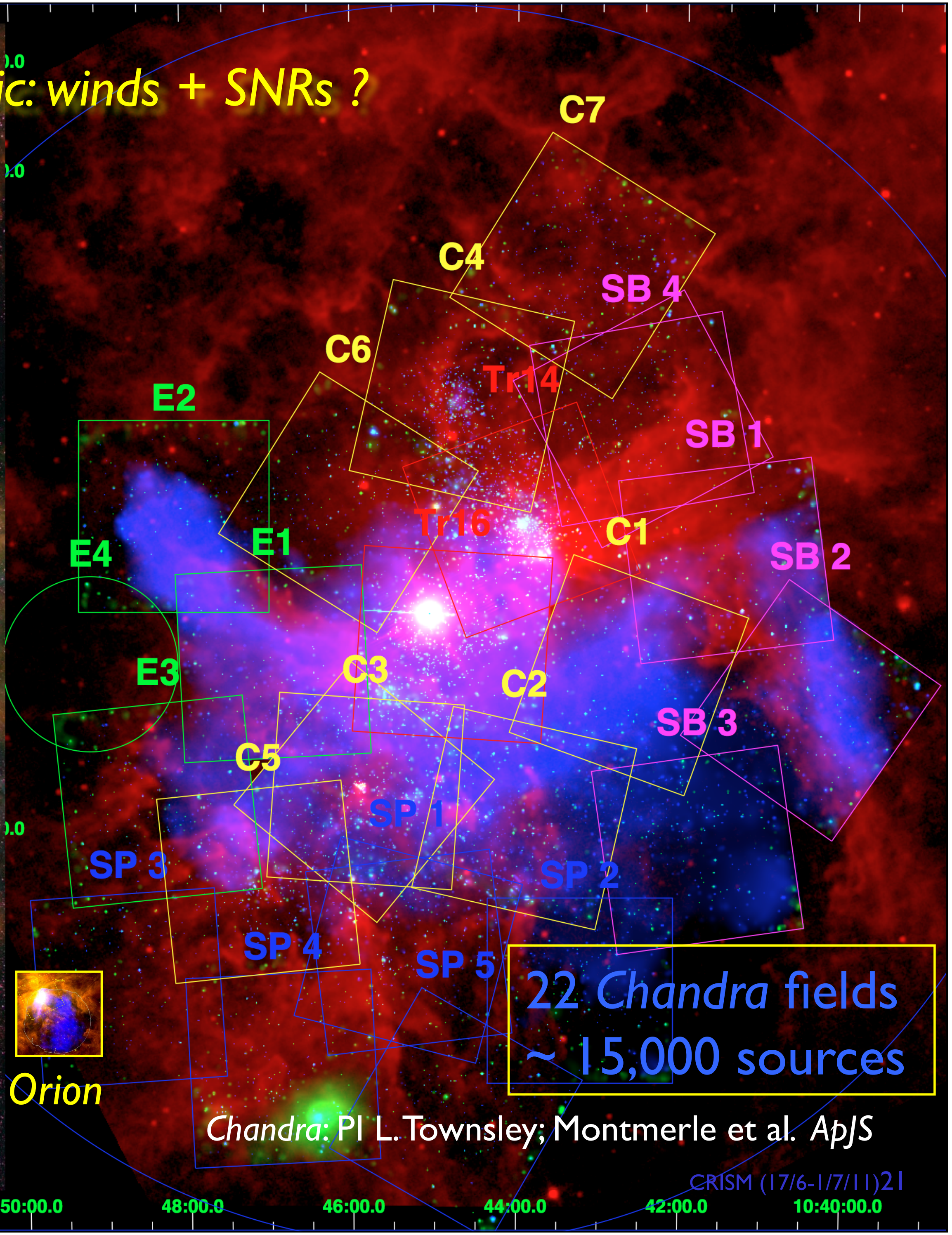
Dunne et al. 2003

The Carina nebula environment



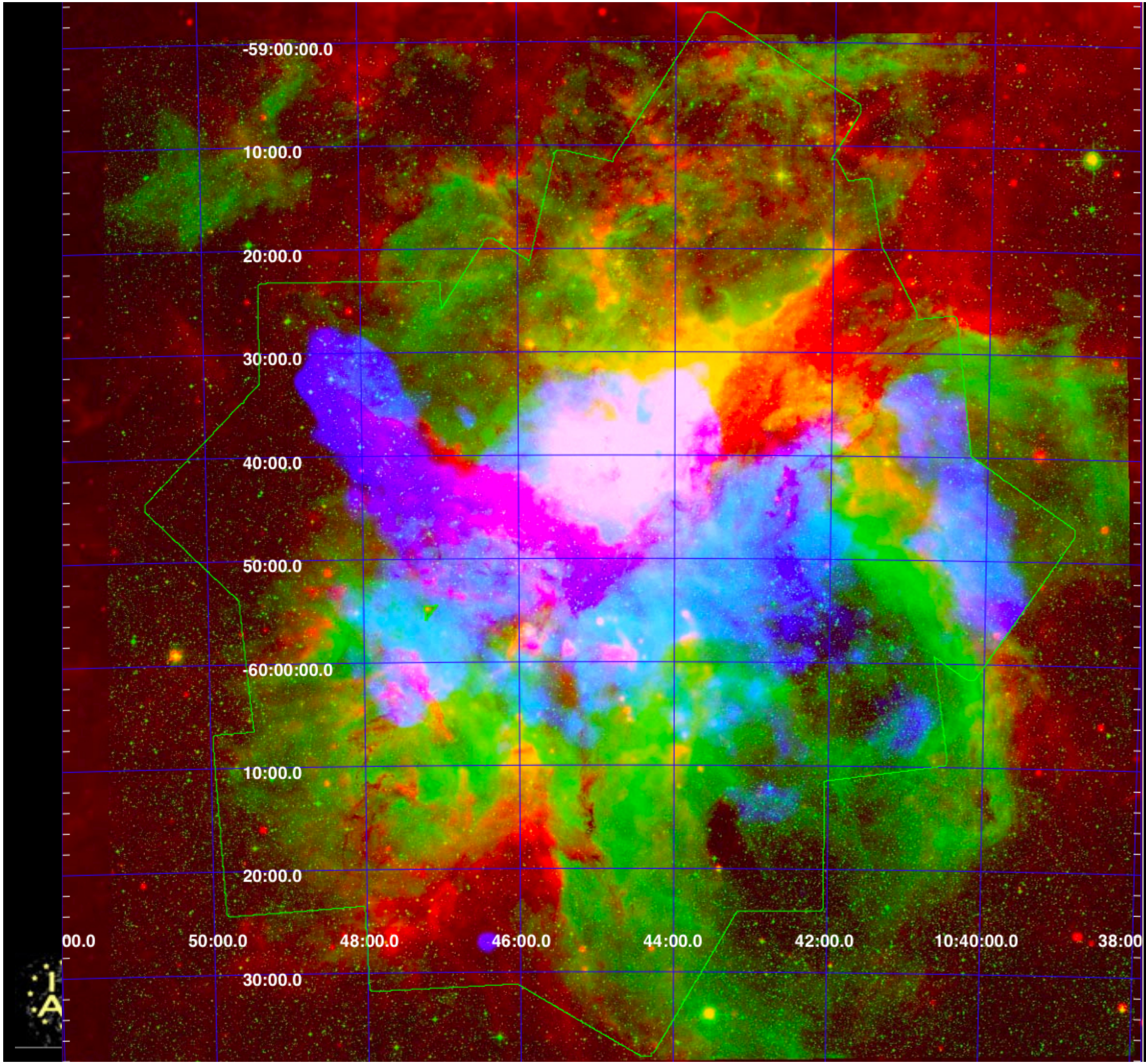
The great Carina X-ray mosaic: winds + SNRs ?





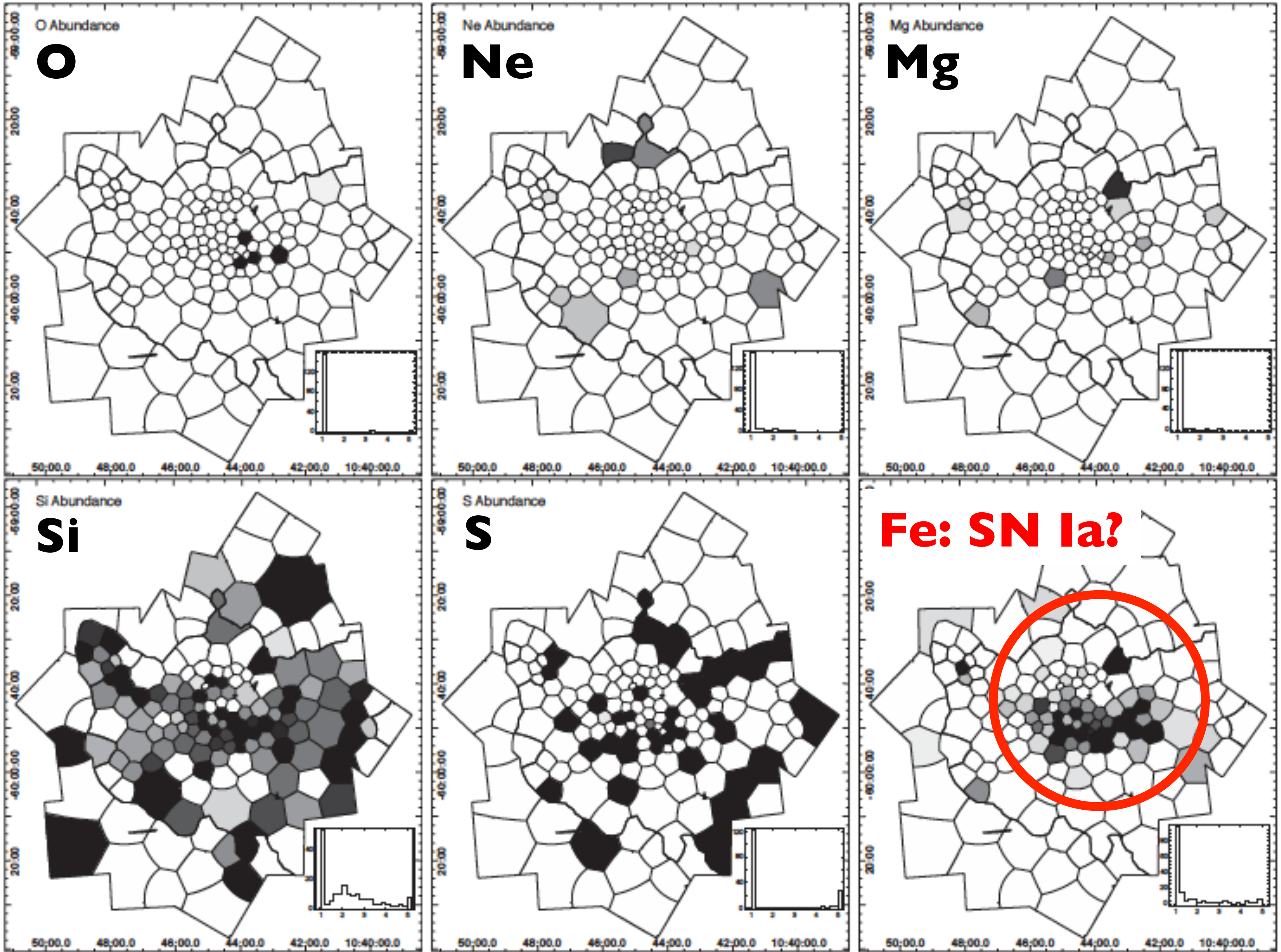
22 *Chandra* fields
~ 15,000 sources

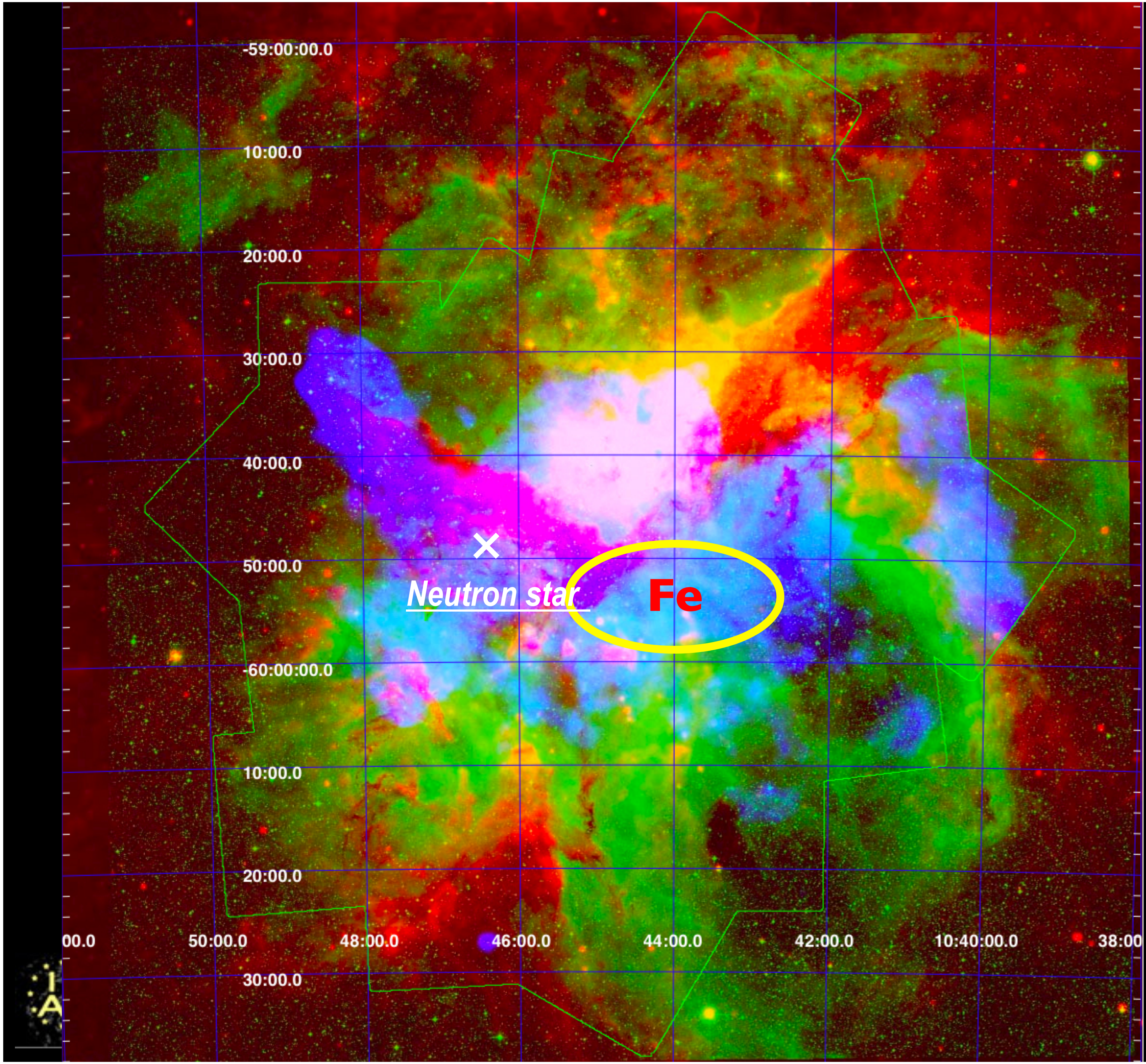
Chandra: PI L. Townsley; Montmerle et al. *ApJS*



DSS (warm gas)
+
MSX8 (dust)

Plasma abundances





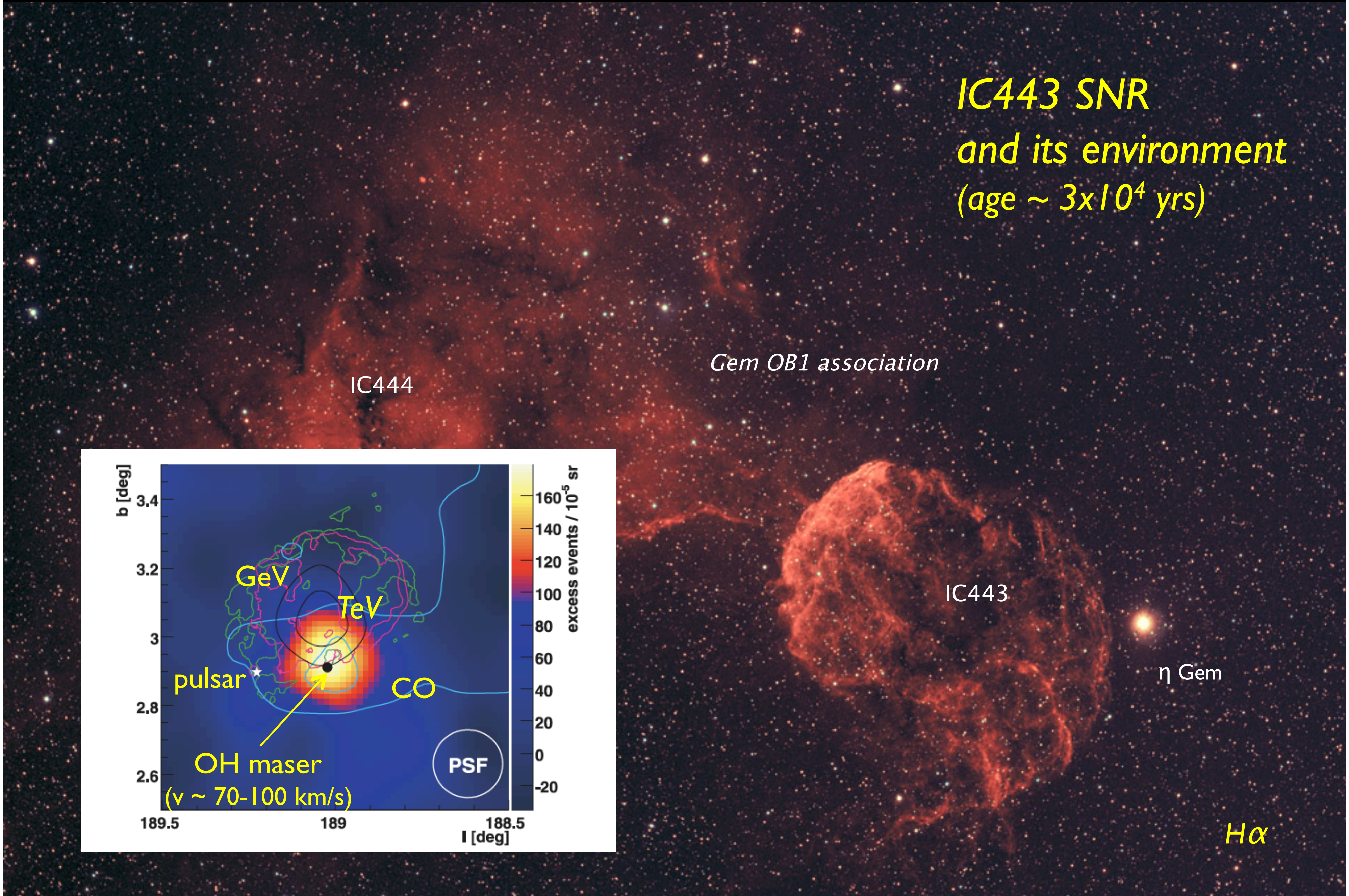
DSS (warm gas)
+
MSX8 (dust)

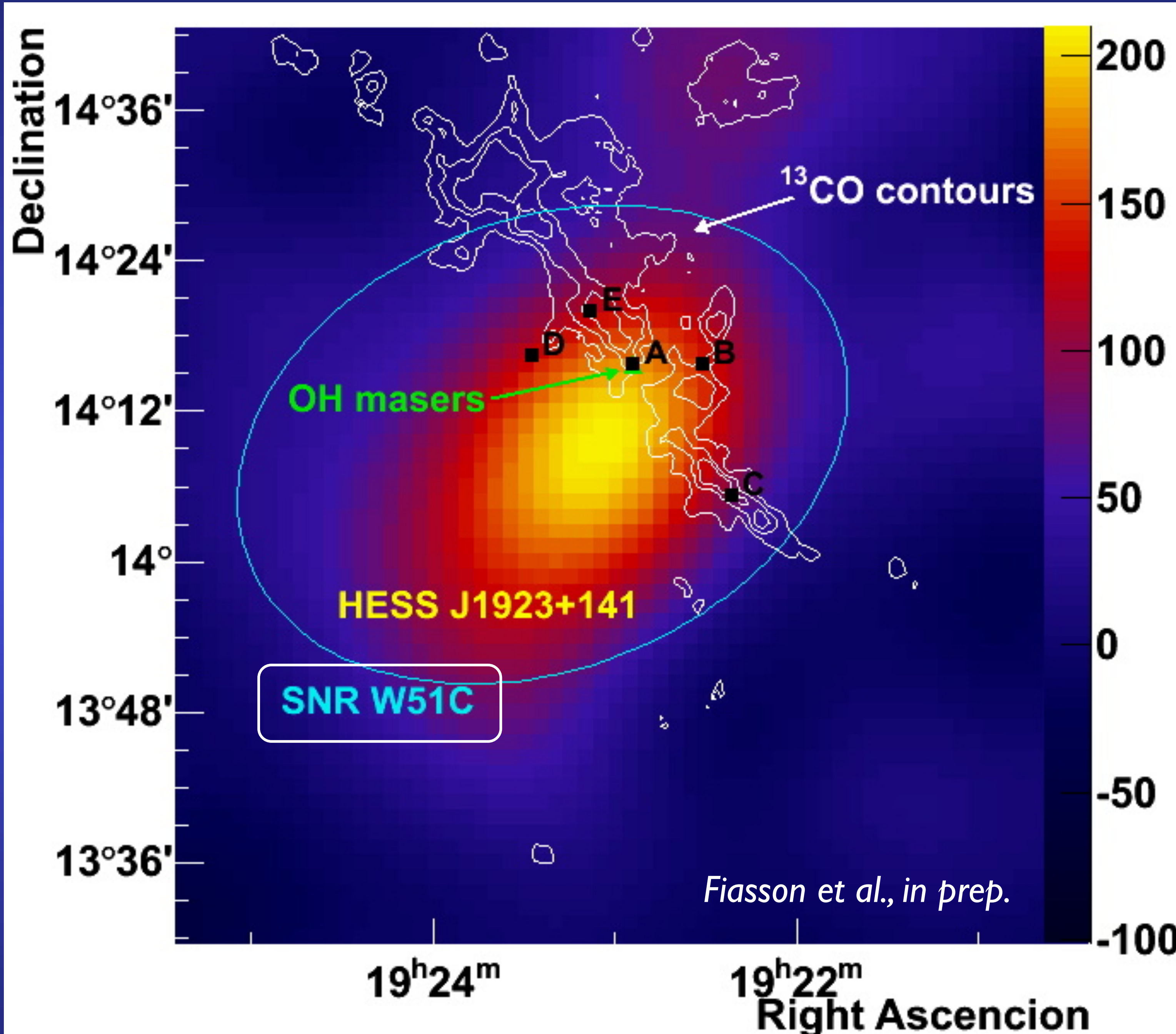
- In spite of the (possible) presence of SNR and of the (certain) presence of intense winds in Carina (and around Orion), no high-energy γ-ray signature of a CR excess
- => if CR are accelerated, they do not penetrate inside the molecular clouds; they are more likely advected by the outflowing hot gas
- => "unfavorable" conditions to observe CR acceleration

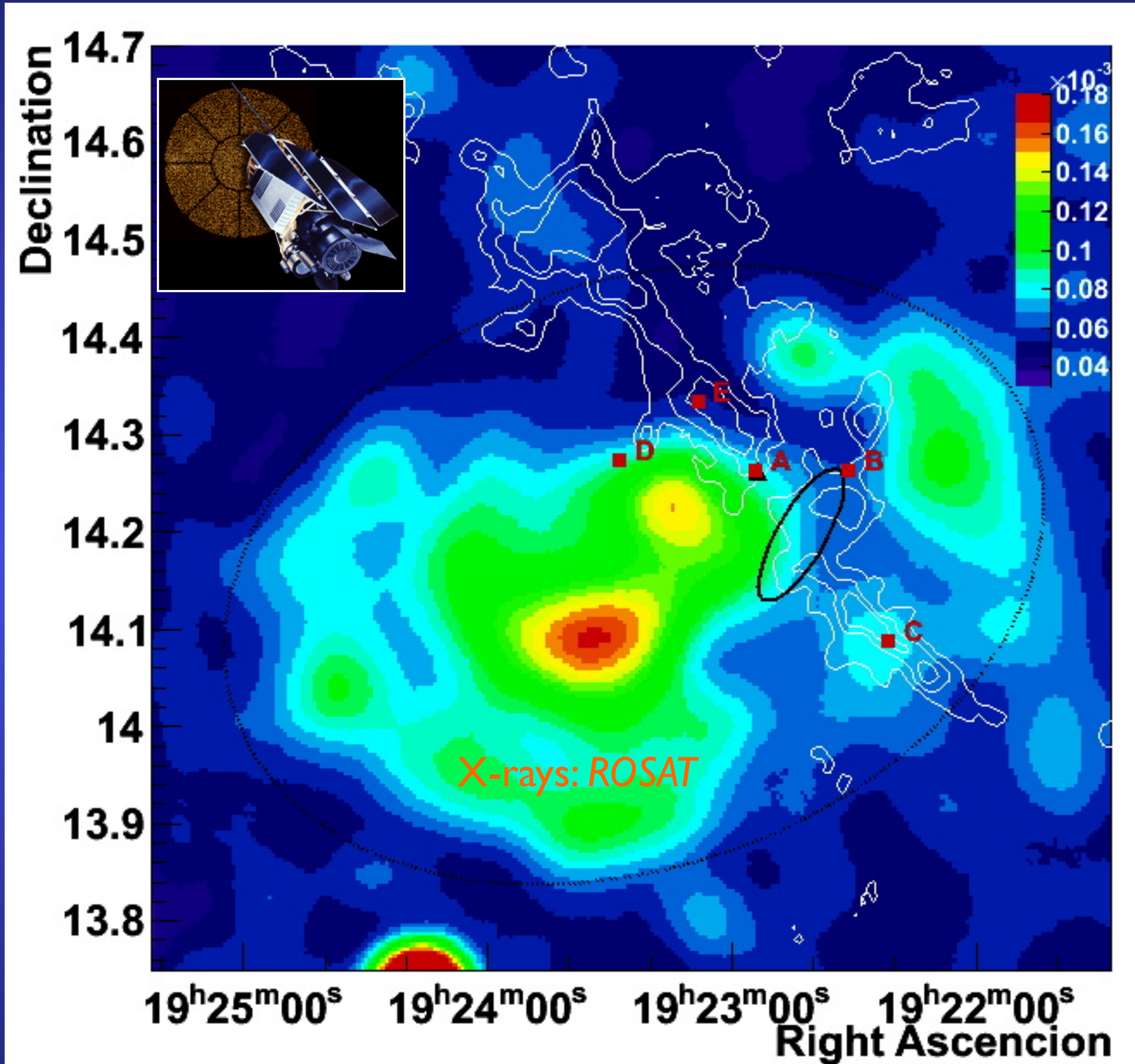
4. Cosmic collisions: Supernova shocks-molecular clouds

IC443 SNR and its environment

(age ~ 3×10^{4} yrs)

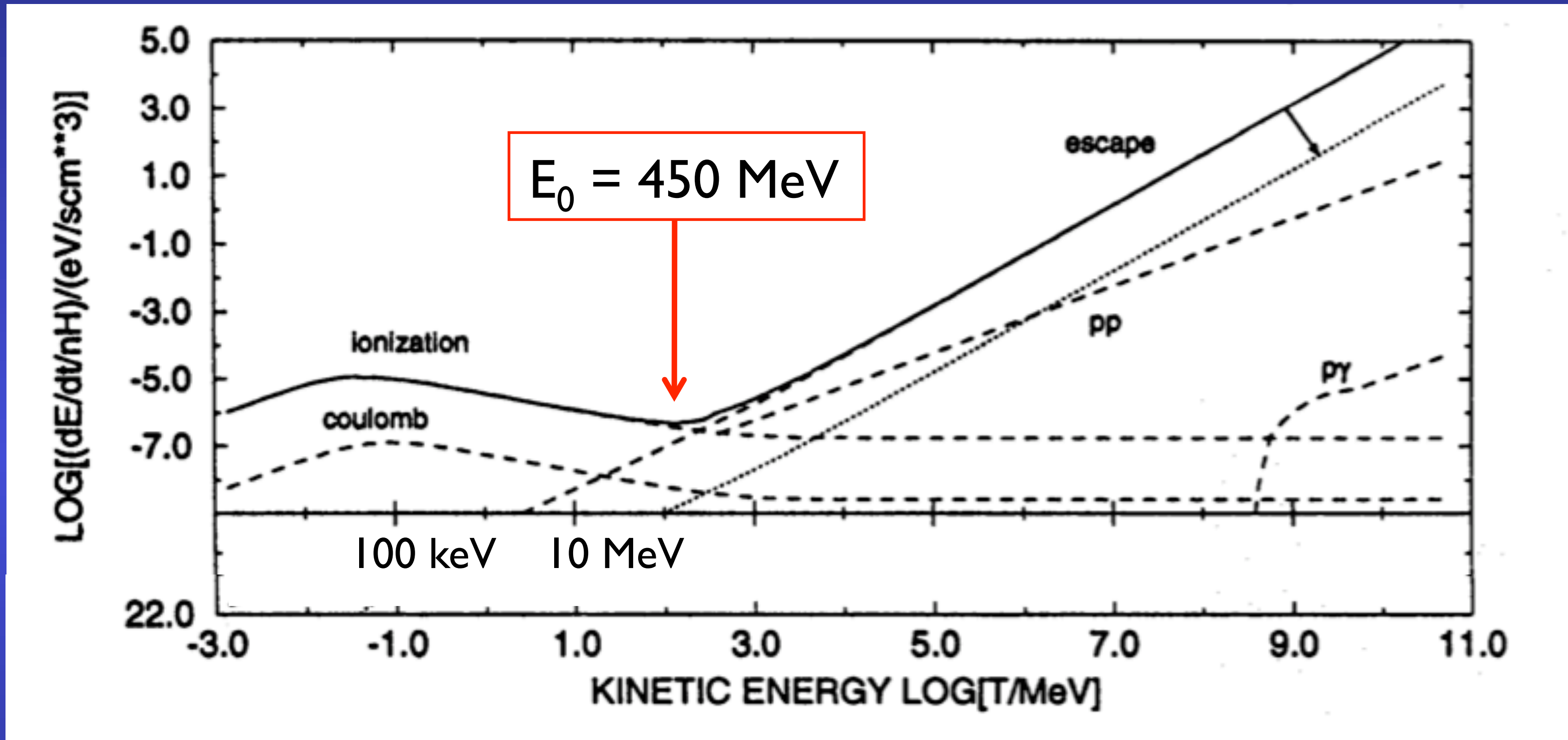



Declination
14°36'
14°24'
14°12'
14°
13°48'
13°36'
19h24m
19h22m
Right Ascencion
200
150
100
50
0
-50
-100
13CO contours
OH masers
HESS J1923+141
SNR W51C
A
B
C
D
E
Fiasson et al., in prep.


Declination
14.7
14.6
14.5
14.4
14.3
14.2
14.1
14
13.9
13.8
$\times10^{-3}$
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
E
D
A
B
C
X-rays: *ROSAT*
$19^h25^m00^s$
$19^h24^m00^s$
$19^h23^m00^s$
$19^h22^m00^s$
Right Ascencion

- ⇔ *Low-energy interactions*
- General idea: assume TeV γ-rays come from > TeV protons (π° decay) accelerated by the SNR shock
- => Enhanced molecular cloud ionization comes from associated low -energy GCR (> 10 MeV-100 MeV)
- => Link with GeV/TeV flux

- => Measure *ionization degree x_e*: local CR flux enhancement
  - Usual value $\zeta_0 \sim 10^{-17}$-10^{-16} s^{-1} => for $n_e \sim 10^4$-10^5 cm^{-3}, $x_e \sim 10^{-8}$-10^{-7} (e.g., Caselli et al. 1998)
  - => important chemical effects (=> H_3^+ ; H_2D^+ ; radicals…)
  - => *role in star formation ?* (+ magnetic fields: ambipolar diffusion)
- *Several methods:*
  - Absorption lines: H_3^+ (NIR: Indriolo et al. 2010)
  - Emission lines: DCO^+/HCO^+
- New: H_2^+ and H_3^+ NIR and FIR emission lines (Becker et al. 2011)



Results ? Listen to Cecilia Ceccarelli ! (Friday morning)

Mannheim & Schlickeiser 1994

Concluding remarks

- The "high-energy view" of the ISM brings new insights into the "life" of massive star forming regions and OB associations:
  - *long episodes* (~ Myr) of wind-dominated activity, interrupted by *short "bursts"* (~ 0.1 Myr) of SN-dominated activity
  - total lifetime depends on the stellar mass distribution (few to 10x Myr)
- Under certain conditions, SNRs may collide with molecular clouds, accelerating cosmic rays, creating a *temporary* source of GeV-TeV γ-rays and enhancing cloud ionization (inducing a peculiar, 2-phase chemistry)
- Other SNRs may explode *within the hot plasma* => induce turbulence and possibly accelerate CR (?), and merge, but the high-energy particles stay *confined* in the hot plasma and do not interact with molecular clouds (e.g., Carina is *not* a γ-ray source !)
- Hot plasmas expand in *superbubbles*: turbulent CR acceleration ? But here also no matter to make γ-rays…