High-speed shocks and X-rays from massive star-forming regions

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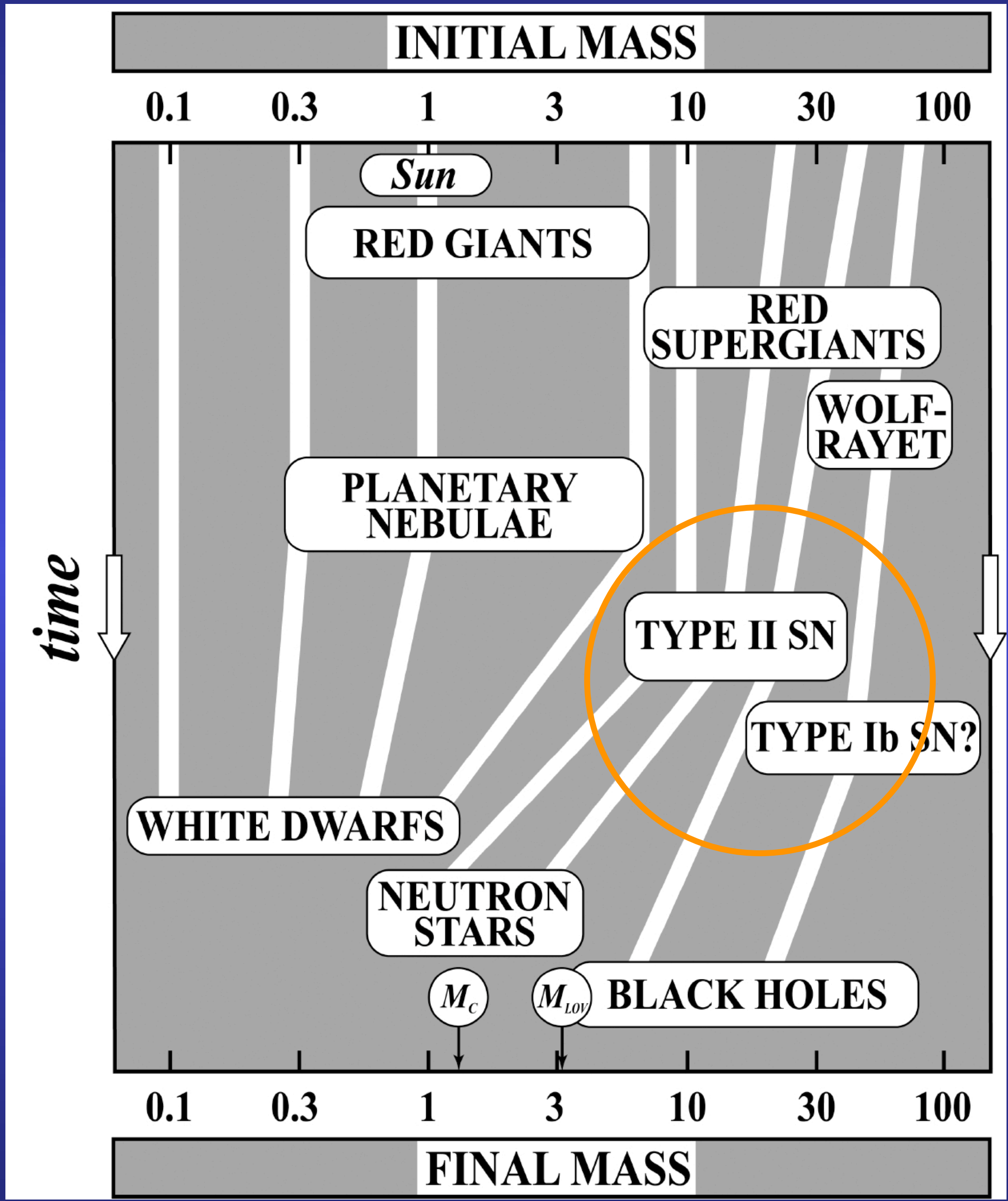
Outline

- 1. Introduction: feedback from massive stars in star-forming regions
- 2. Supernova remnants: the X-ray view
- 3. Wind bubbles: search & discovery
- 4. Nucleosynthesis: high-energy diagnostics
- 5. Superbubbles
- 6. Consequences: cosmic-ray irradiation effects
- 7. Conclusions

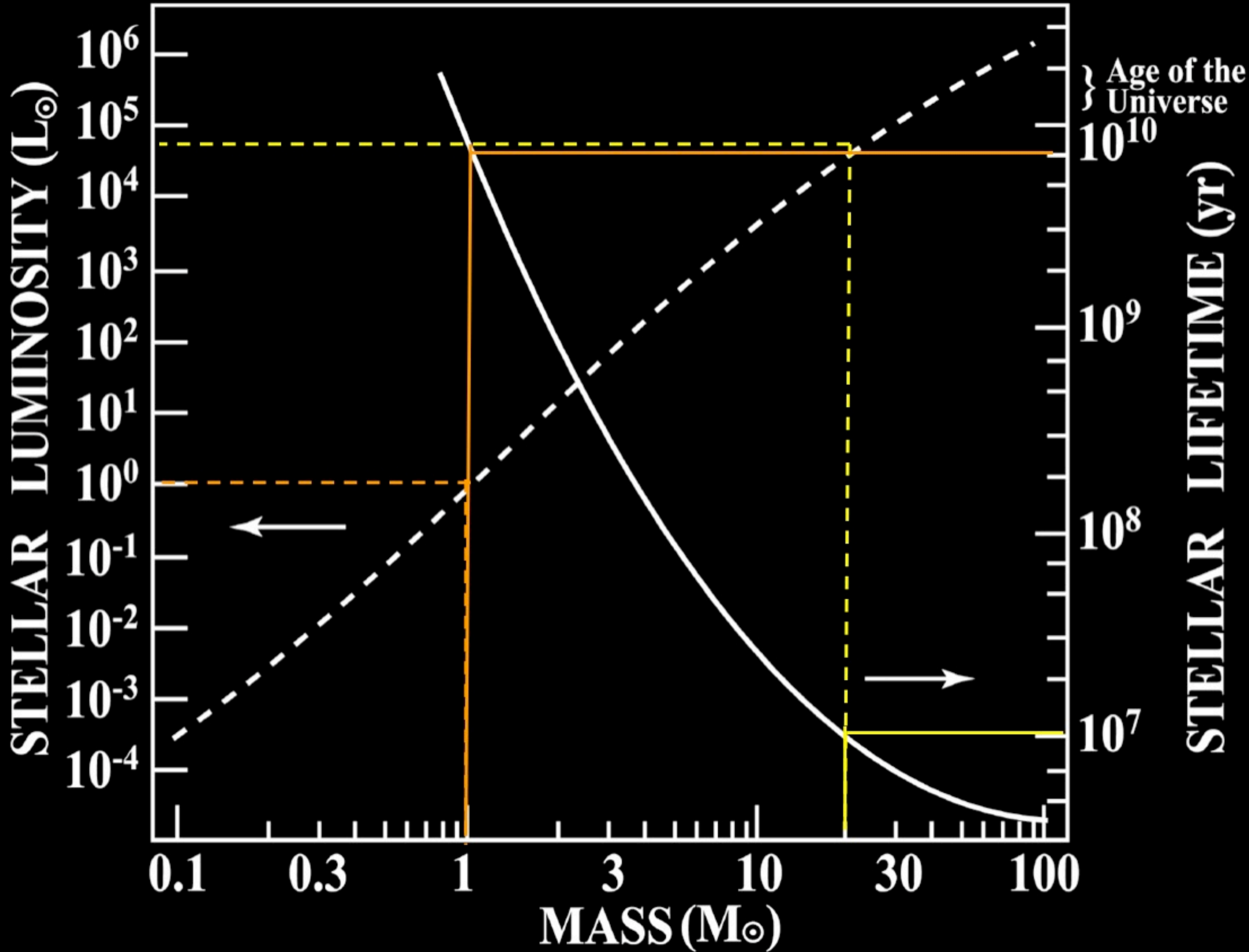
1. Feedback effects

- Key factor:
  - Short stellar lifetime (< 10 Myr) for $M_* > 20\text{-}30\ M_a$
  - End up as type II (= core-collapse) supernovae, i.e., *while still in their parent SFR*
- During all their lives, produce very strong stellar winds (~ x10 at the ~ 10^5 yr pre-SN, WR stage):
  - O stars: $M_{dot} \sim 10^{-6}\text{-}10^{-5}\ M_a/yr$
  - $V_\infty \sim 1000\text{-}3000$ km/s
  - Energy budget: $E_{tot} = \int E_w\, dt \sim 10^{51}$ ergs
    - => $E_{tot,w} \sim E_{SN}$
- => Continuous (x Myr) high-speed kinetic energy injection into the SFR (winds) + short-lived "spikes" (SN: x 1-10 kyr) => continuous supply of X-ray plasma ("bubbles")

Stellar destinies…



Stellar lifetimes



The "Initial Mass Function"

Salpeter (1955) + more recent studies, in particular towards small masses ("brown dwarfs", $M_* > 0.08\ M_a$)

$$\frac{dN_*}{d\,log M_*} \propto M_*^{-1.5}$$

$$M_{min} \sim 0.5\ M_a$$

$$M_{max} \sim 10\text{-}100\ M_a$$

Ex: Orion

$M_{max} \sim 50\ M_a \Rightarrow N_* \sim 1000$

2. X-rays from SNRs

SNR evolution in (very) brief

- "Sedov" phase: the star material expands at very high velocities (initially up to 20,000 km/s), then slows down (still ~ x 1,000 km/s) as ISM material fills in the expanding shell
  - => high T, high L_X ($L_X/L_{sh} \sim 10^{-3} – 10^{-4}$)
- End of Sedov phase when $M_{ISM} \sim M_*$
  - « snowplow phase »
  - Usually a few 1000-10,000 yrs
  - Cooling by adiabatic expansion (+ radiative: X-rays)
- Radiative phase when pre-shock high-n ISM encountered
  - Shock becomes isothermal and stalls; cooling ~ 10^6 yr ("hot ISM")
- *X-ray signatures all along*

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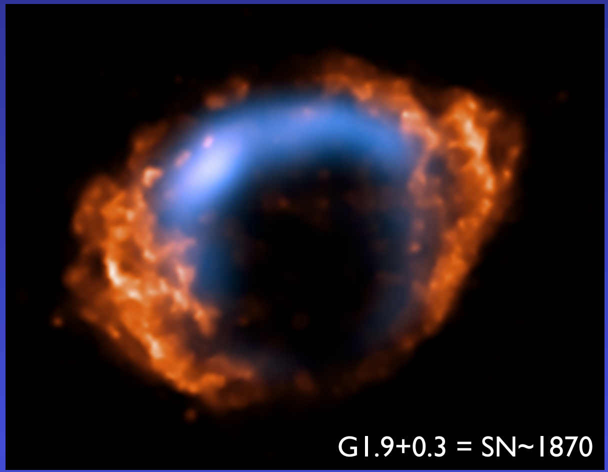
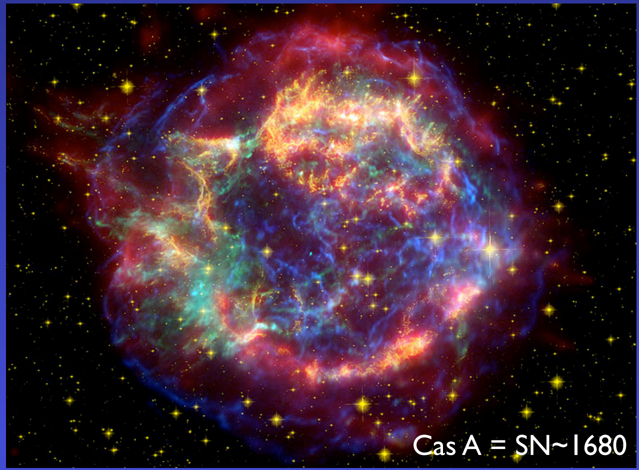
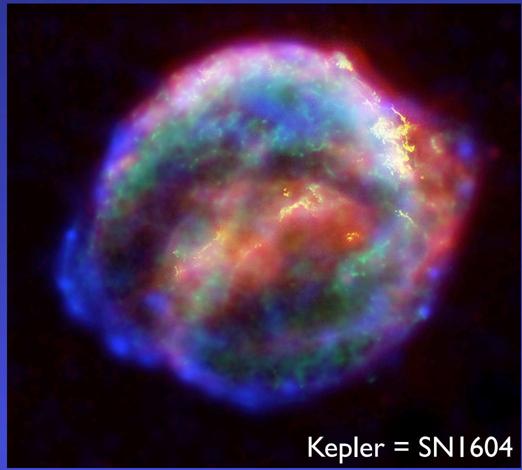
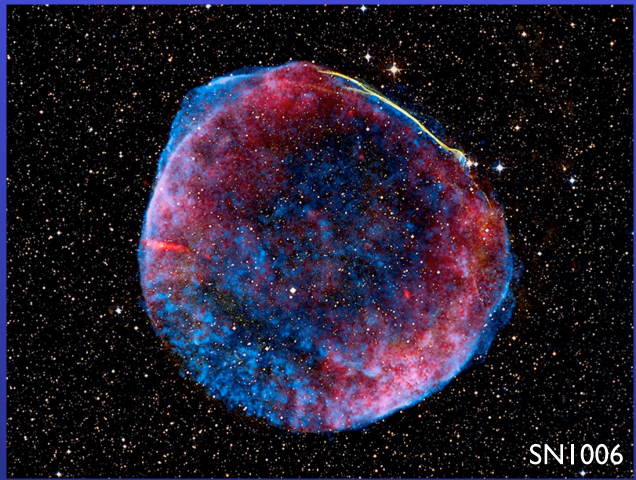
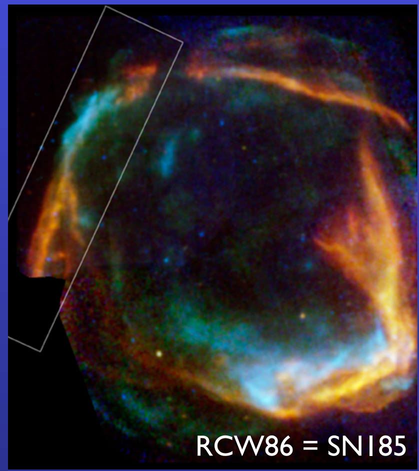
"Historical" supernovae (age < 2000 yrs)



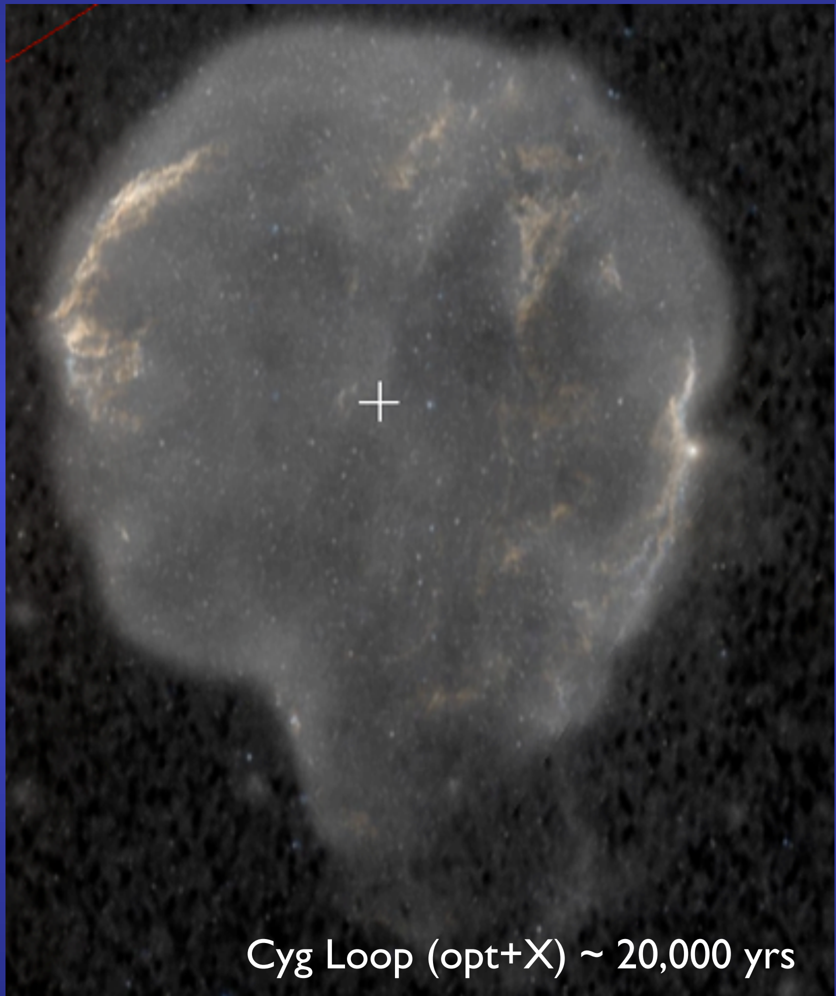


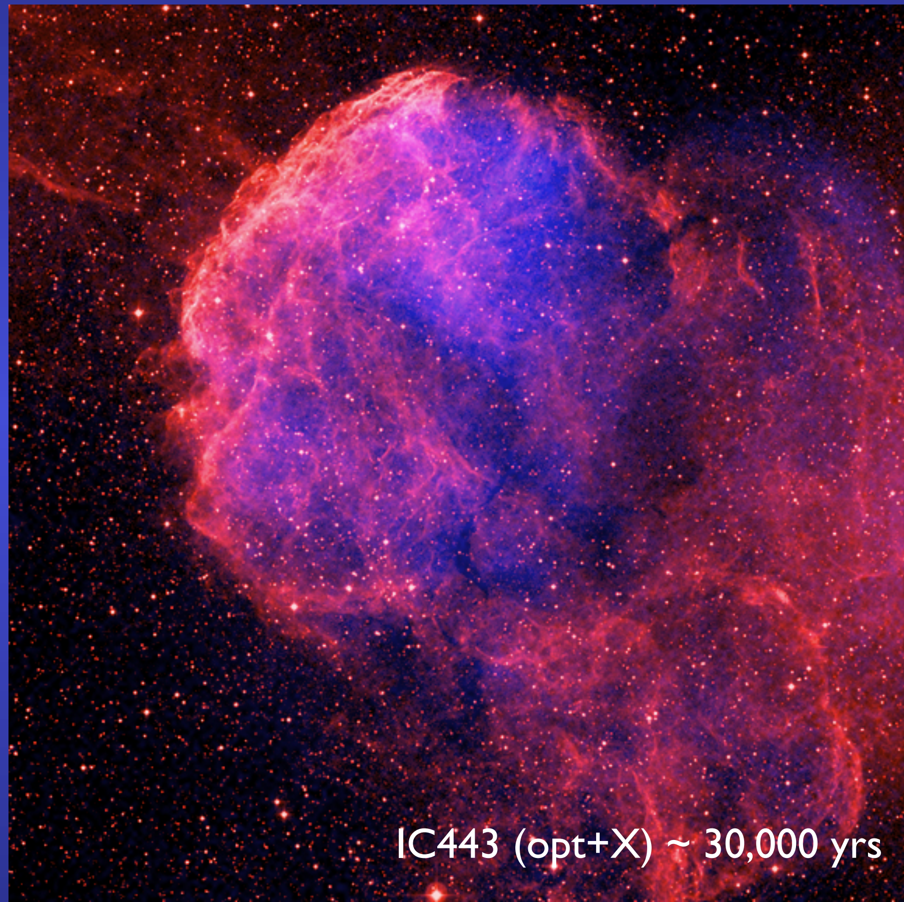






Post-Sedov SNR (> ~ 10^4 yr)





3. Wind bubbles: search & discovery

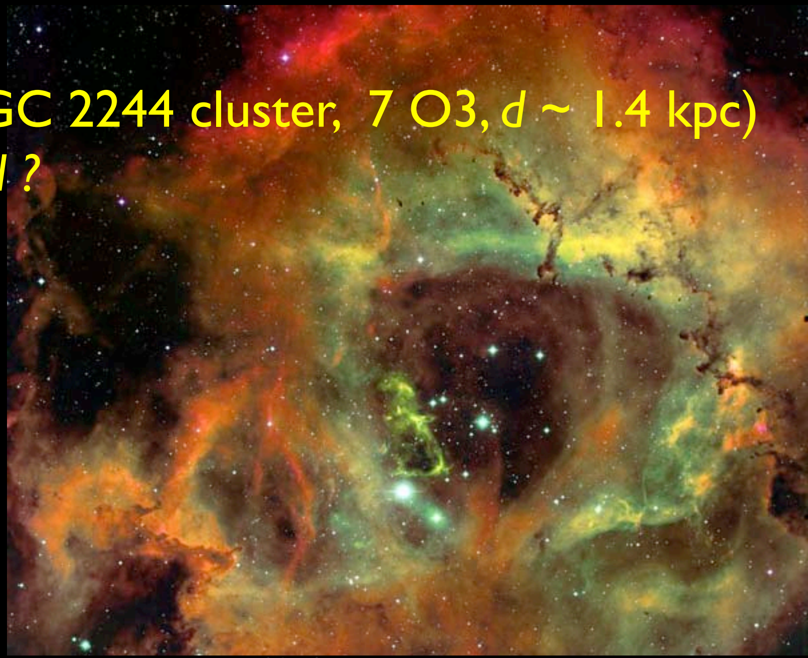
History…

- Theory: X-ray bubbles predicted by Castor et coll. (1975, 1977), following UV discovery (*Copernicus*) of winds from massive stars (« CAK » model, 1975):
  - Treatment like an « inverted supernova »
  - Pb: size HII bubbles >> than observed (ex.: Rosette)
  - New mechanism(s) for energy dissipation at shock ?
  - => *the bubble puzzle*

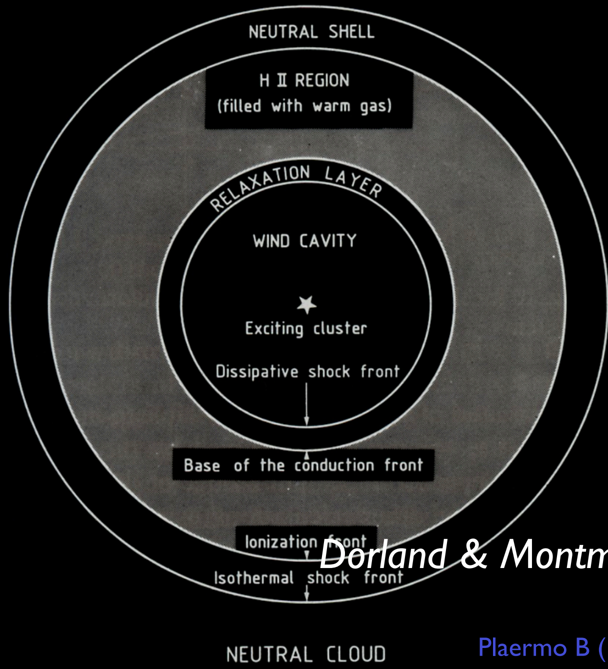
- Observation: very difficult
  - Spatial confusion (*Einstein* resolution ~ 1')
  - X-ray Contamination by x1000 low-mass stars
  - Low surface brightness (<< SNRs)

Rosette nebula (NGC 2244 cluster, 7 O3, *d* ~ 1.4 kpc)

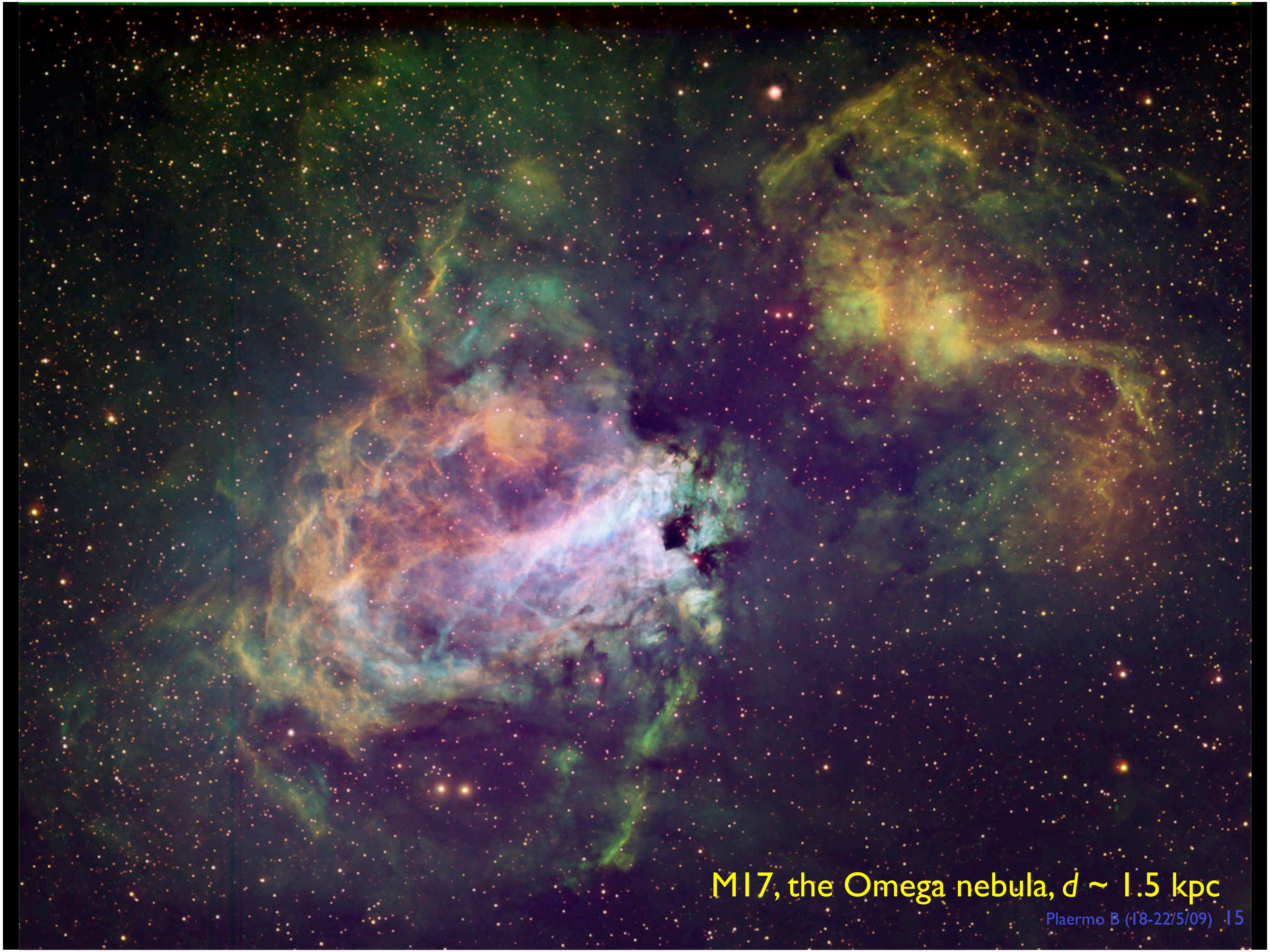
Spherical, closed shell ?



Weaver et al. 1977

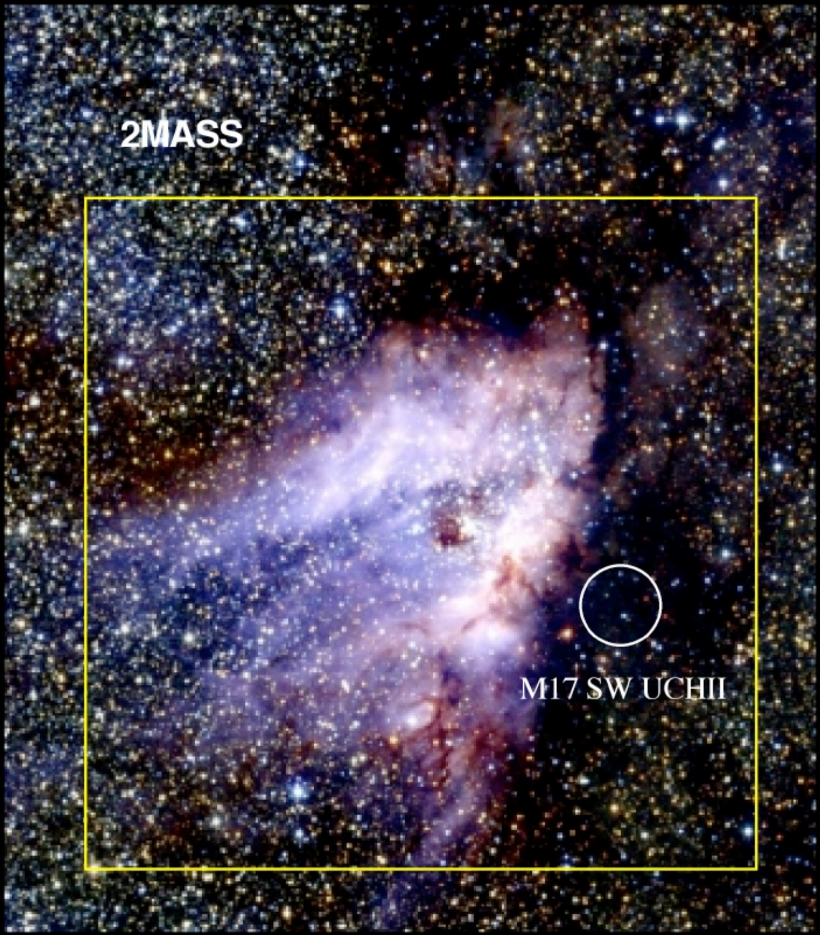


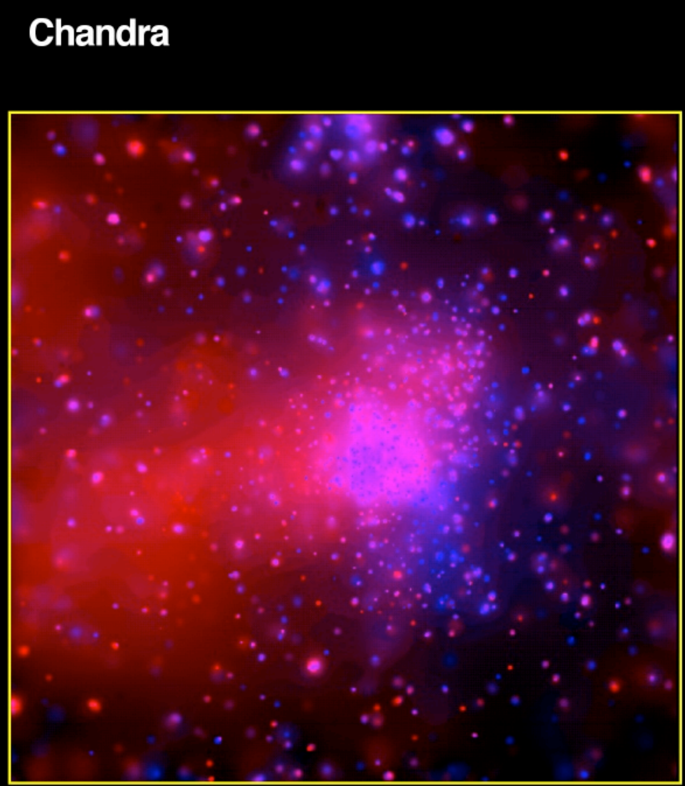
Dorland & Montmerle 1987



M17, the Omega nebula, $d \sim 1.5$ kpc

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

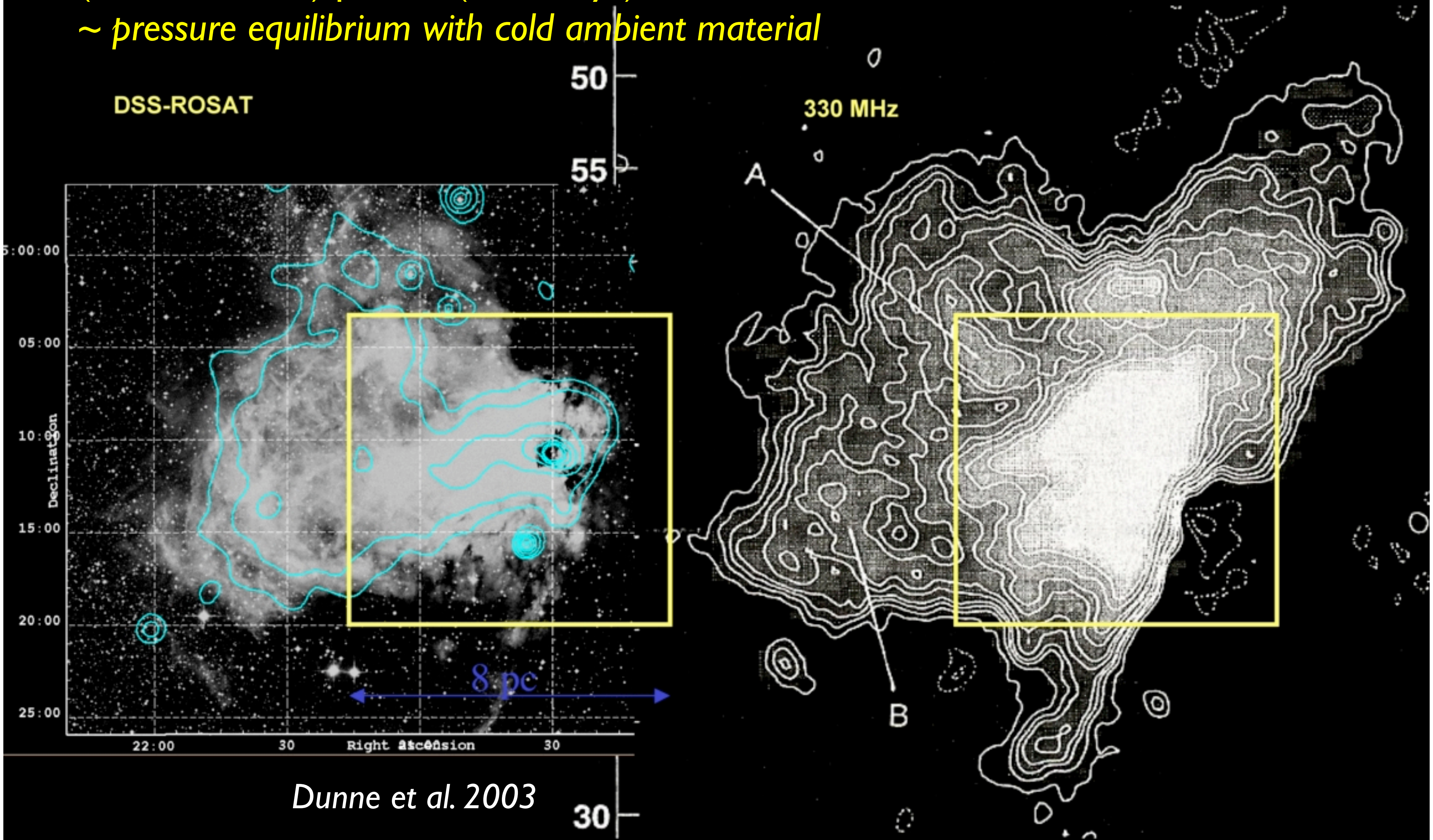




Townsley et al. 2003

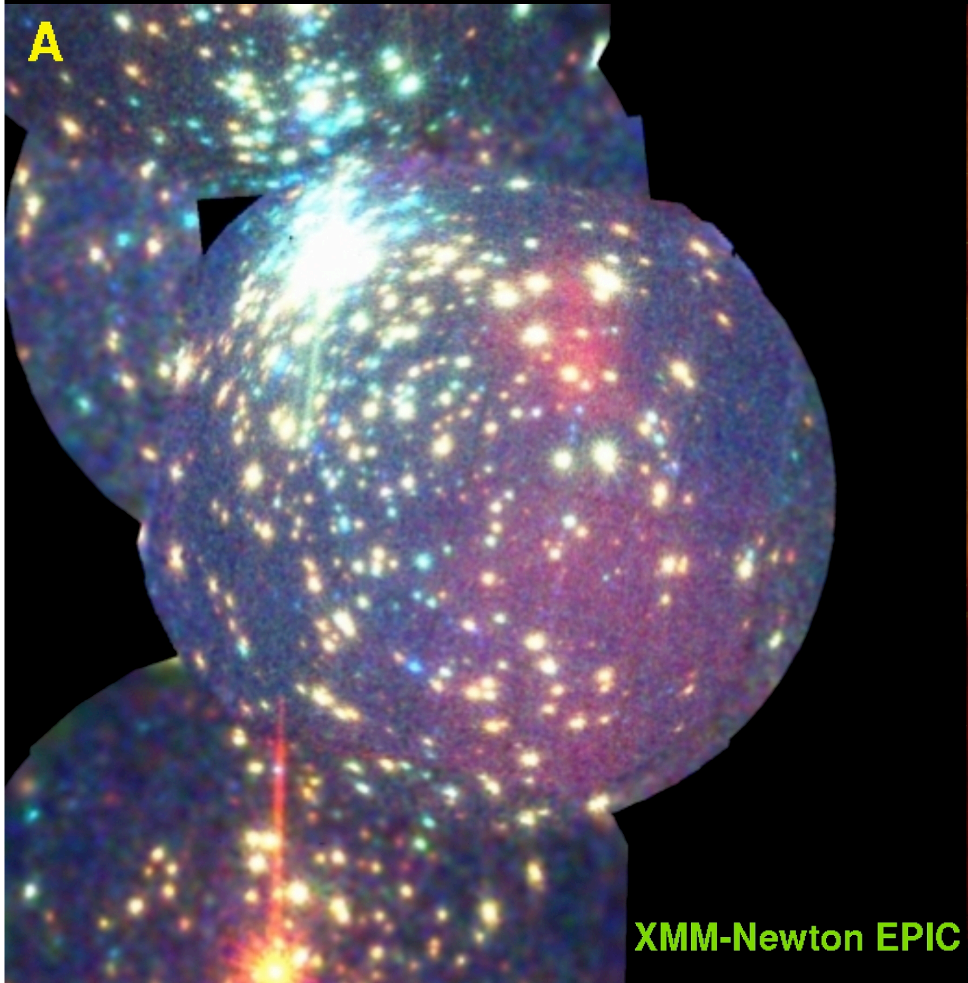
d ~ 2 kpc, ≥ 13 O (O3–>O9.5) + 34 B + x 1000 T Tauri stars (wind-shocked) plasma (⇔ X-rays) flow into the ISM…

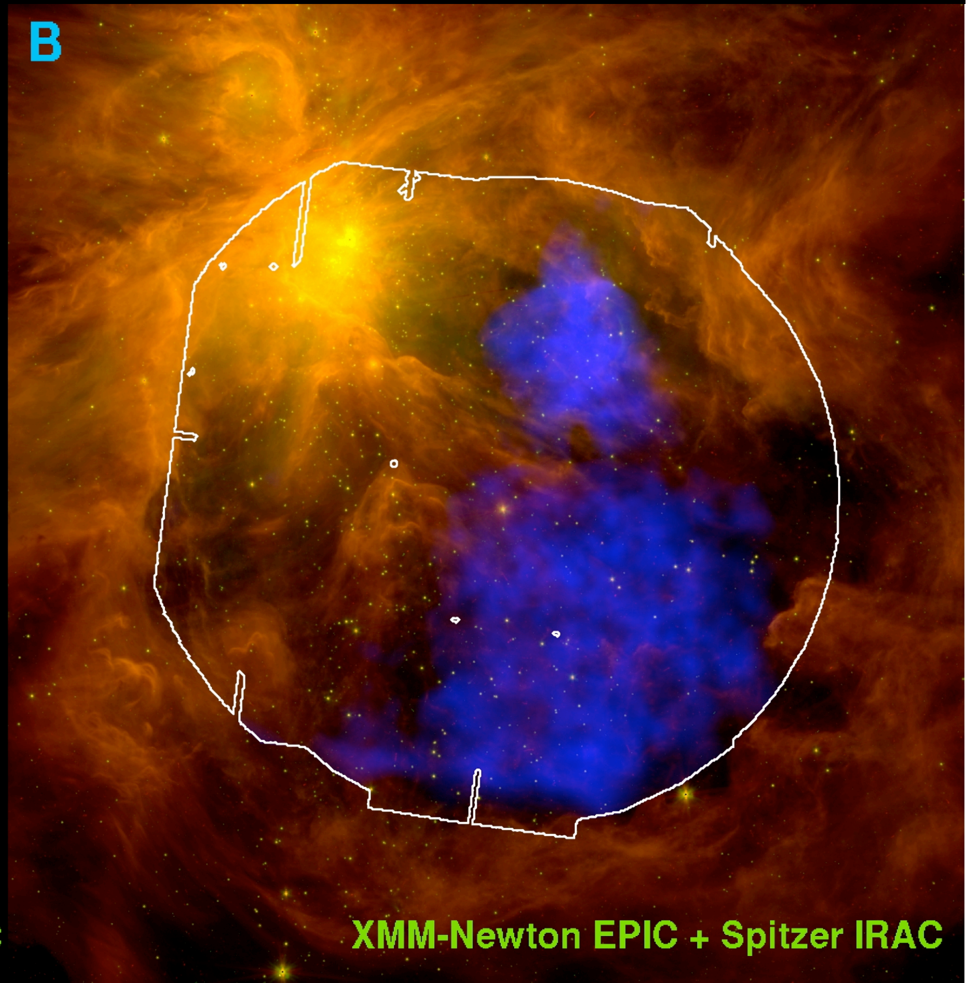
~ pressure equilibrium with cold ambient material

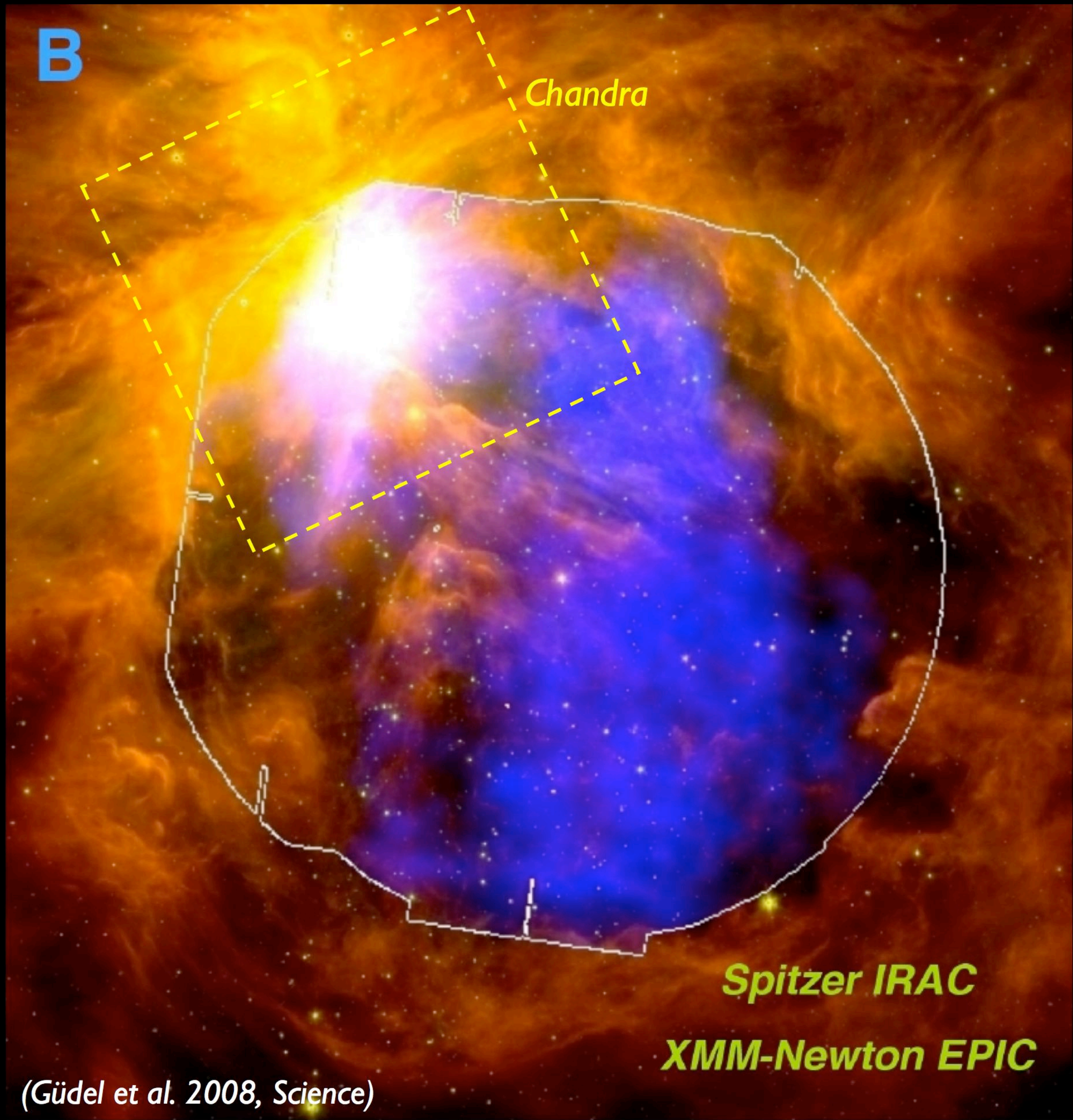


Dunne et al. 2003

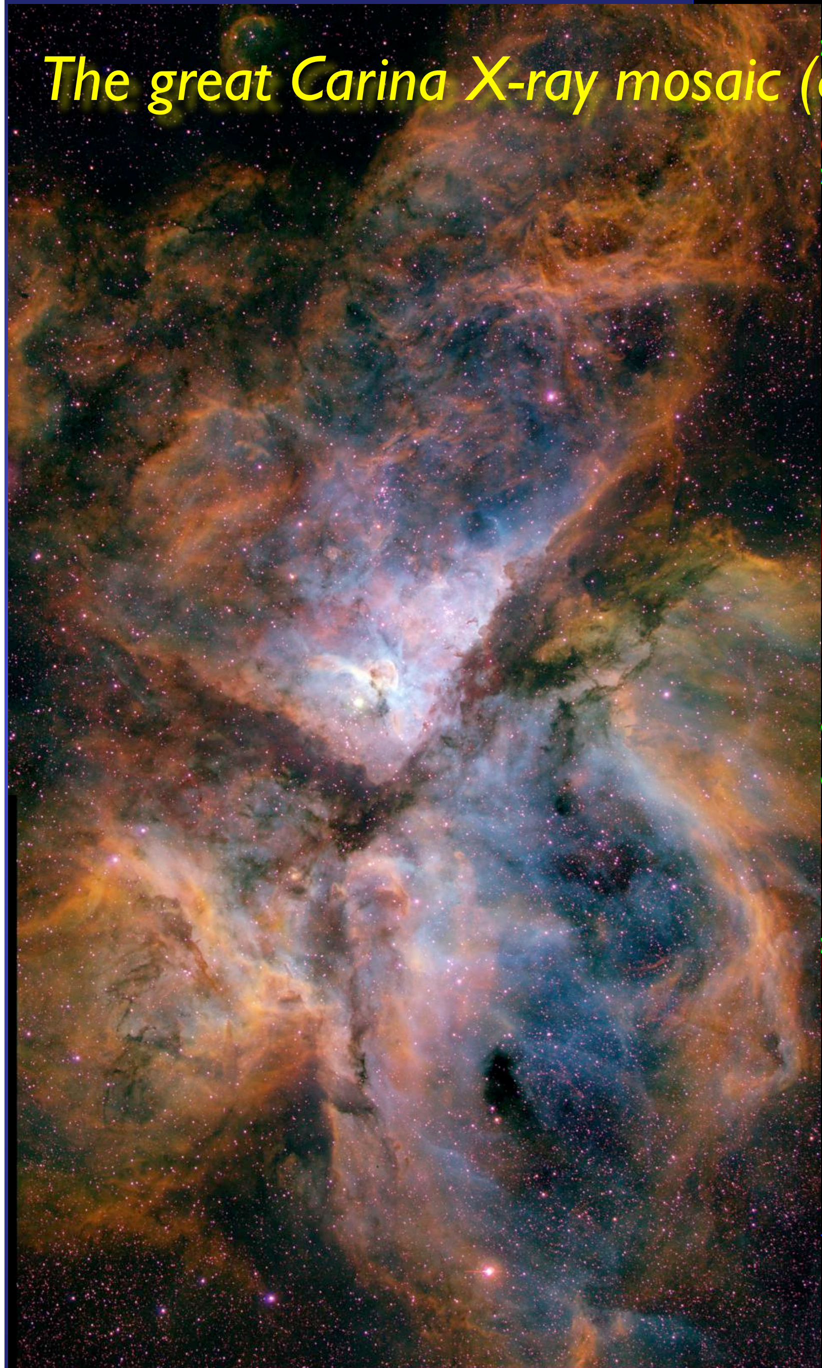
Diffuse soft X-ray emission filling the "Extended Orion Nebula" cavity

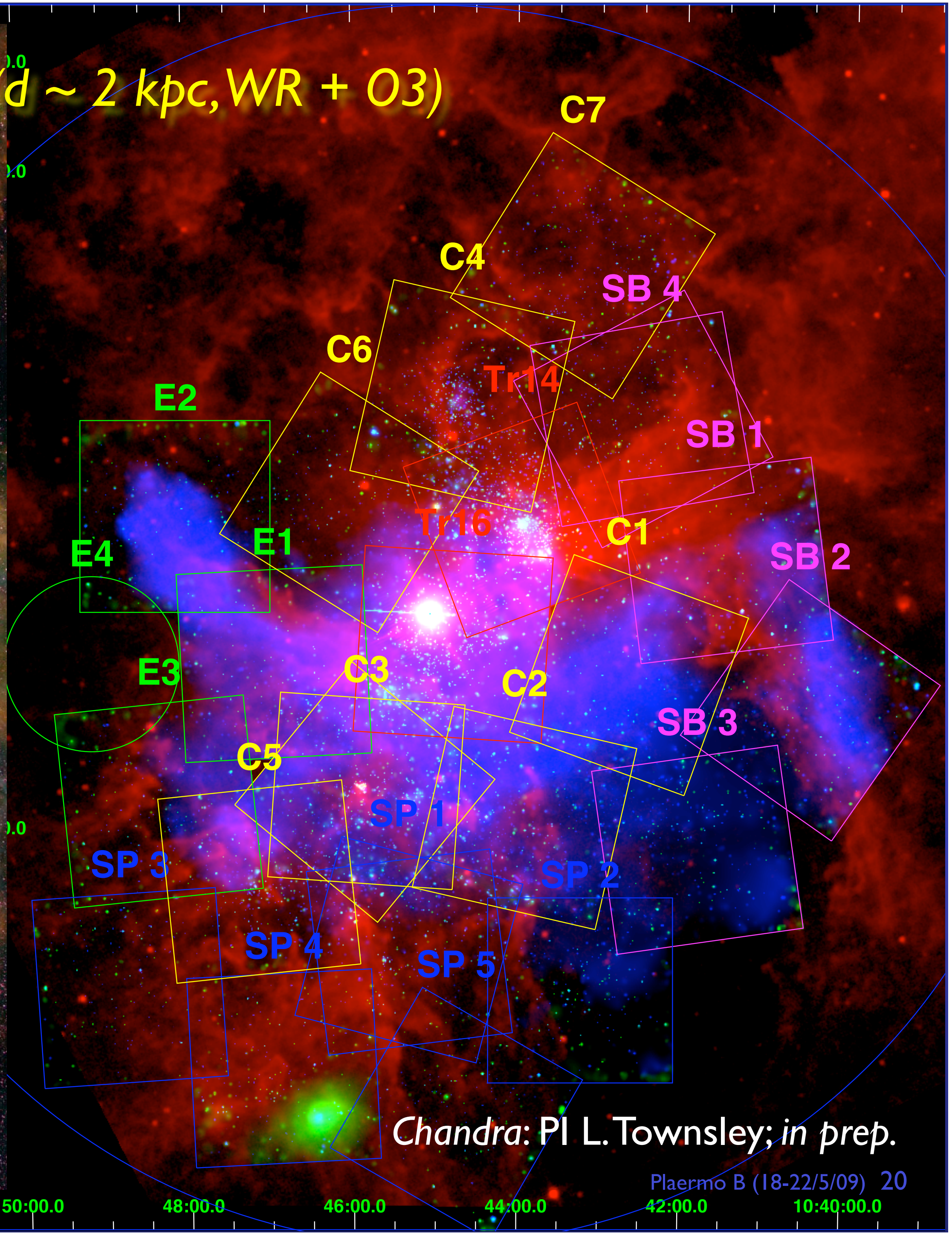




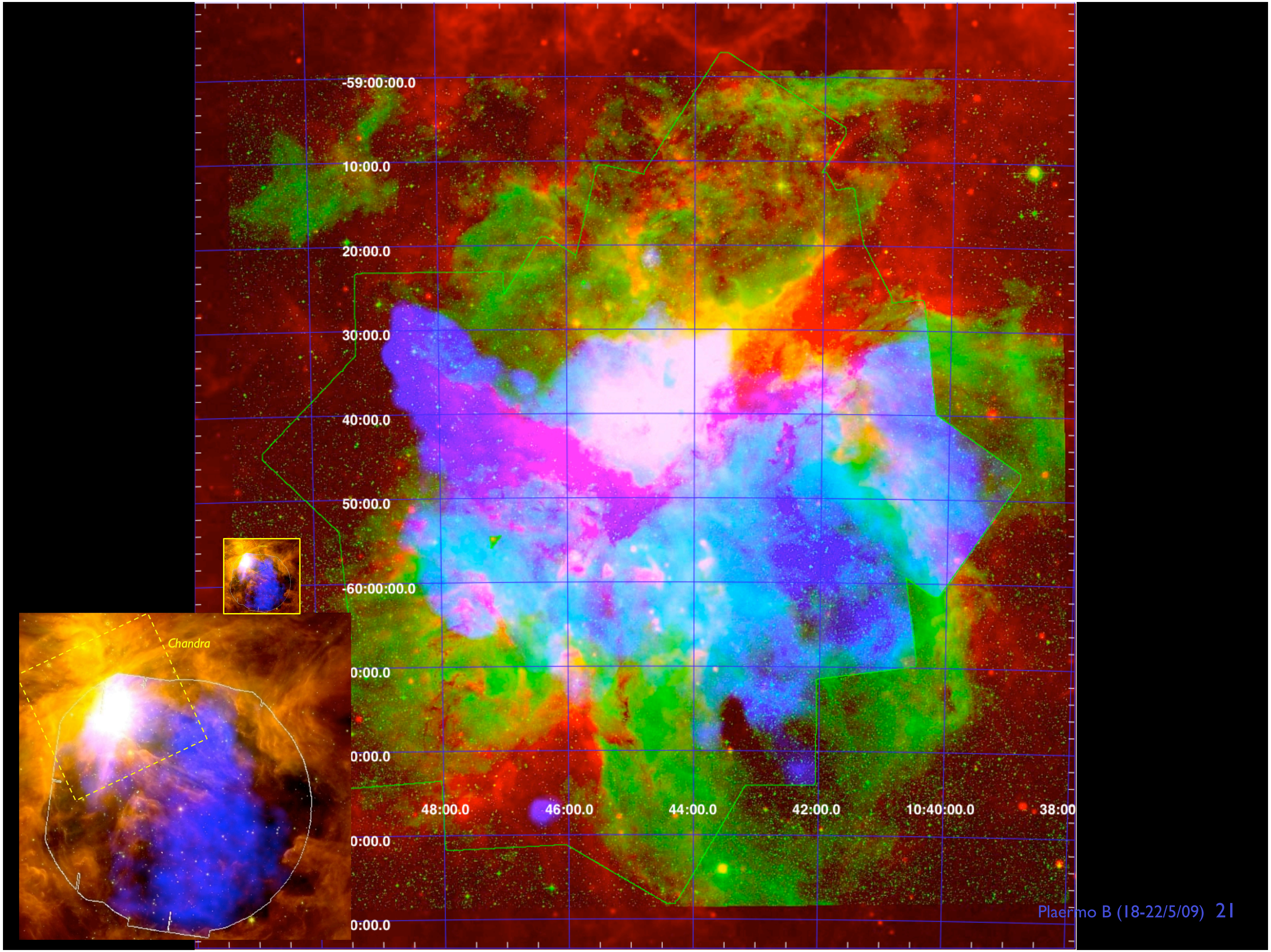

B
Chandra
Spitzer IRAC
XMM-Newton EPIC
(Güdel et al. 2008, Science)

The great Carina X-ray mosaic (d ~ 2 kpc, WR + O3)





Chandra: PI L. Townsley; *in prep.*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10:00.0
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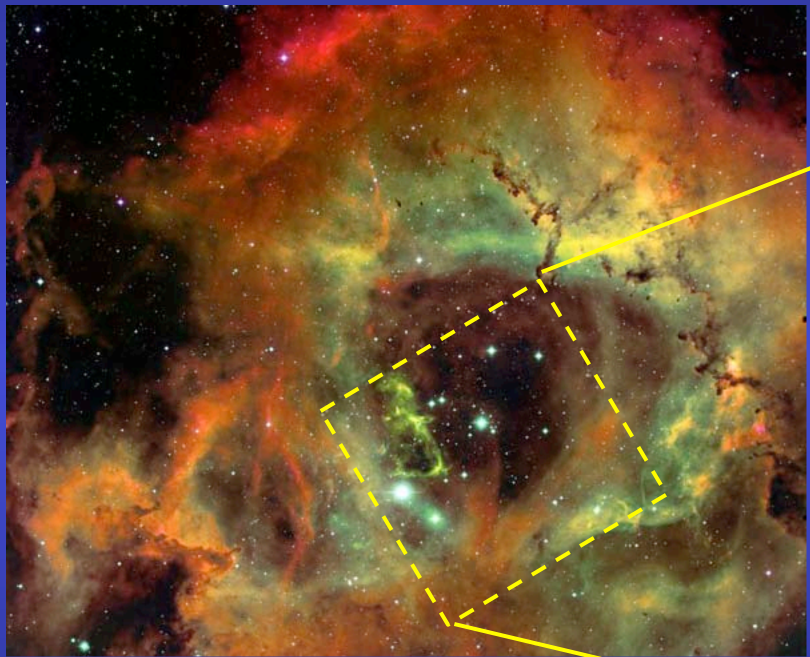
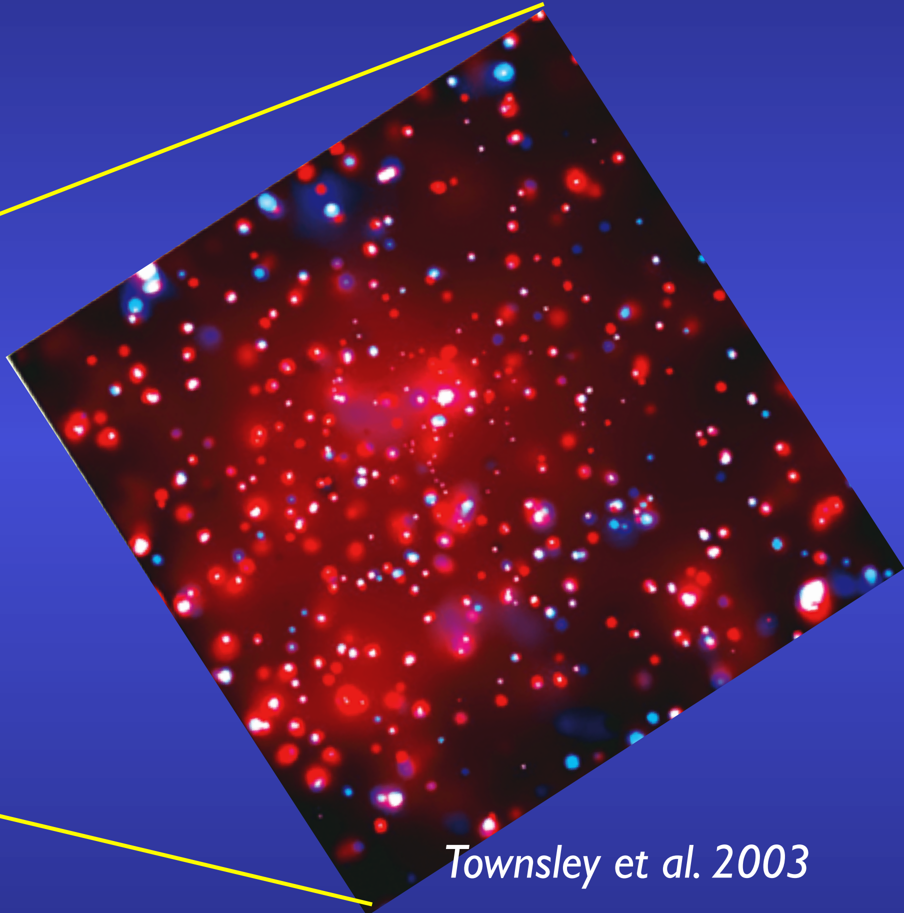
0:00.0
0:00.0
48:00.0
46:00.0
44:00.0
42:00.0
10:40:00.0
38:00
Chandra

The solution to the « bubble puzzle » ?





Townsley et al. 2003

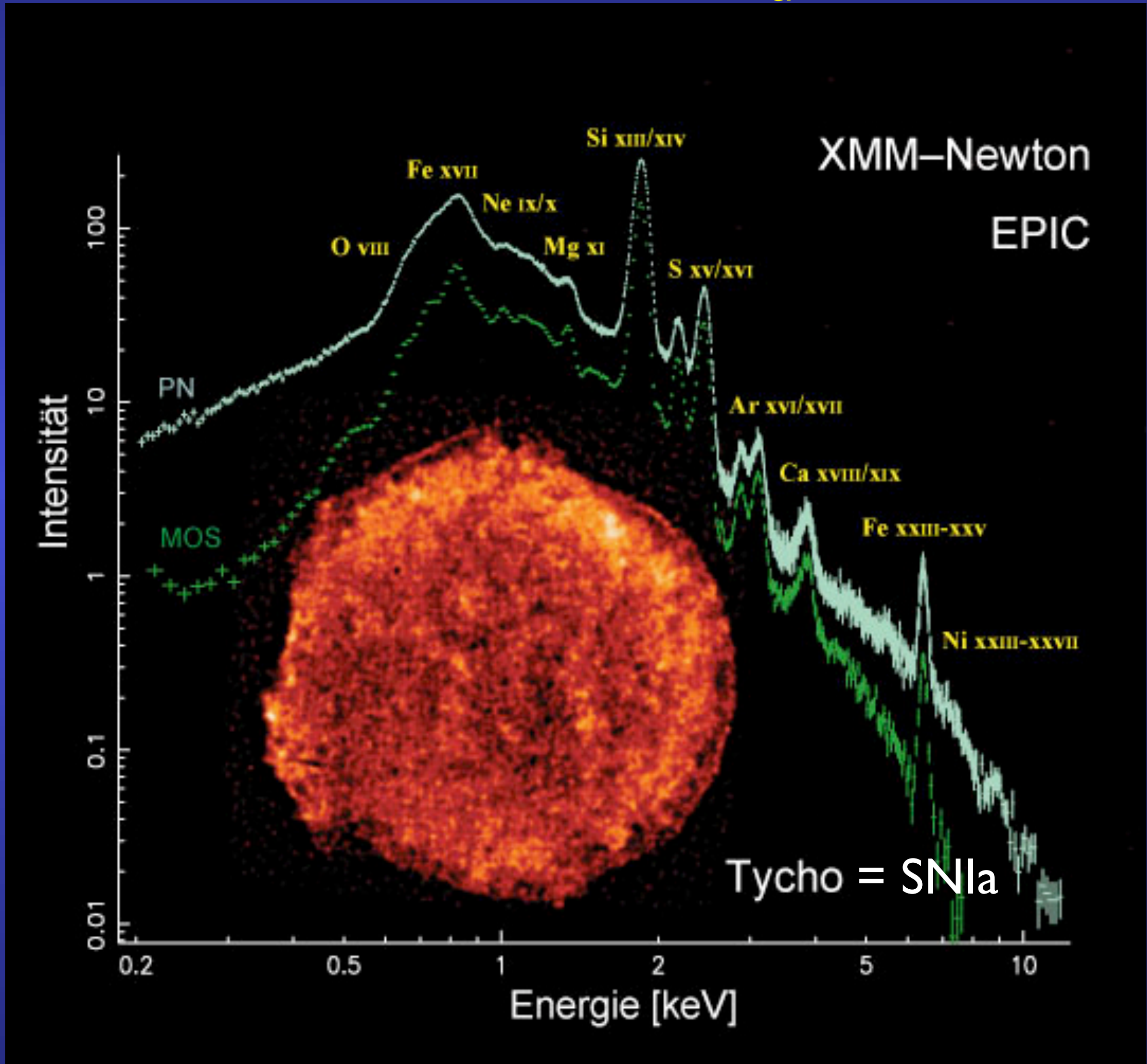
The Rosette bubble… is not a bubble !

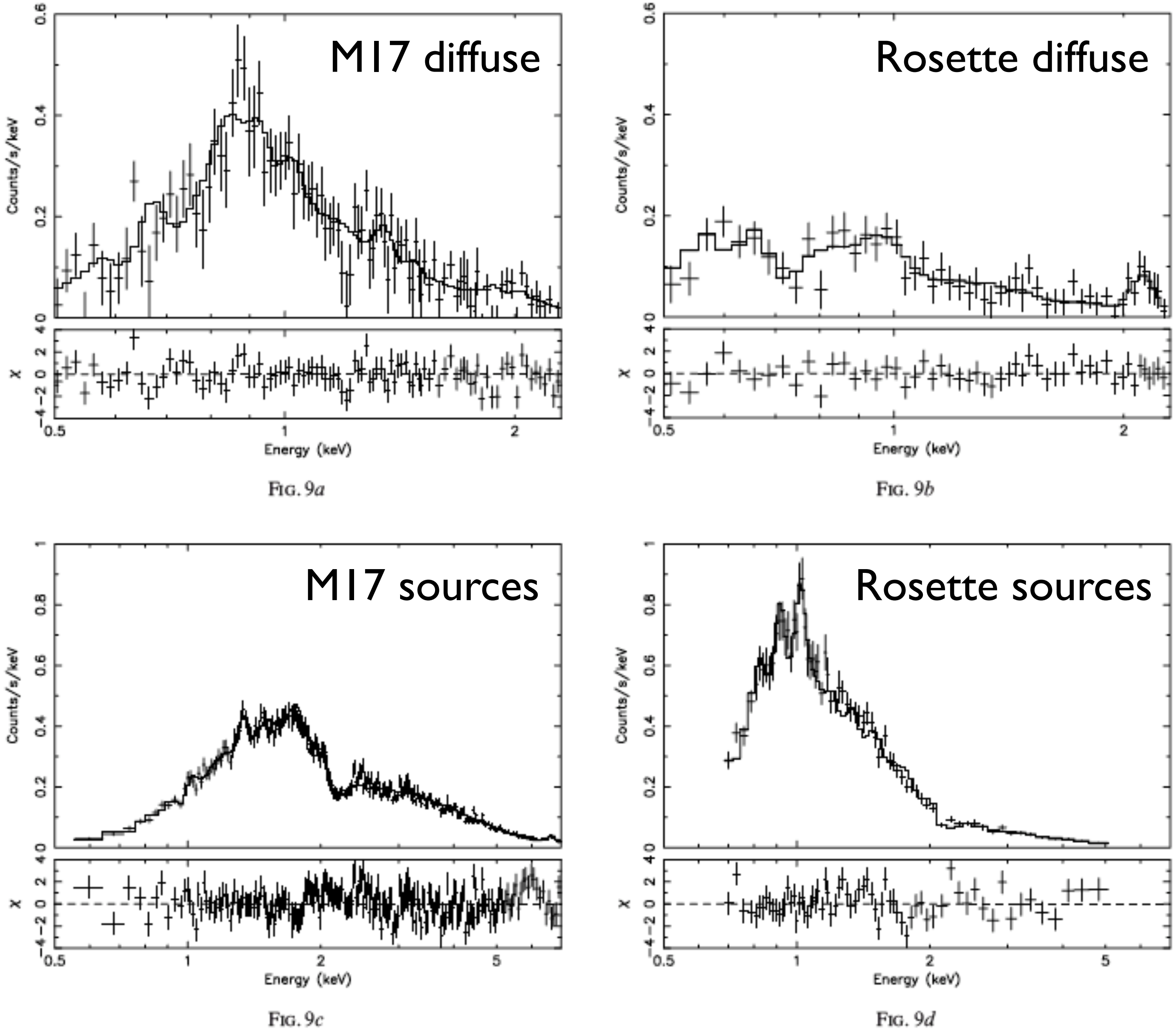
The cavity is open, and plasma flows away ("champagne flow" from "bowl" ?) !

(But XLF => ~ 40% of « diffuse » emission is due to unresolved low-mas stars…)

4. Plasma abundances: X-ray and γ-ray diagnostics

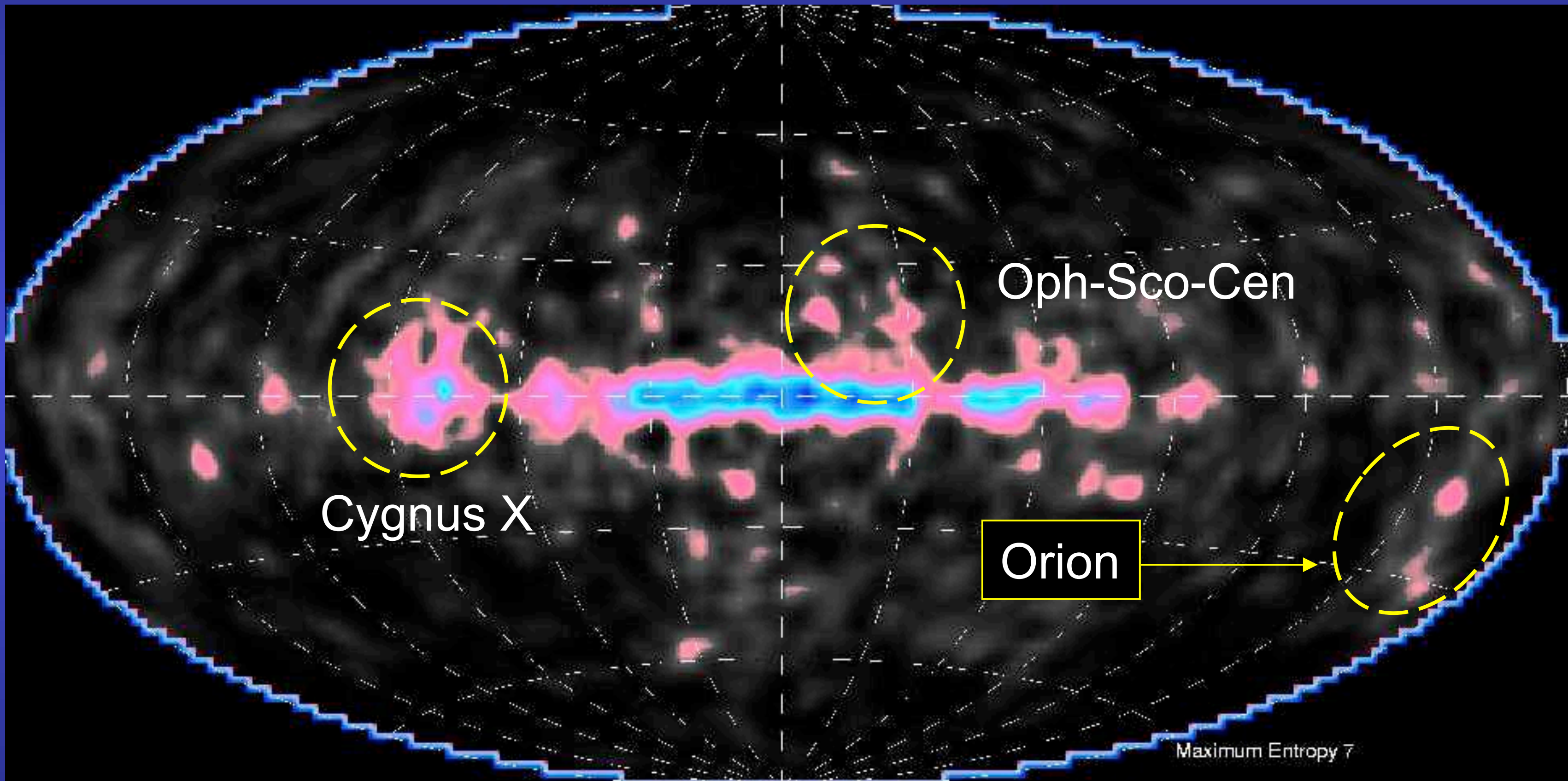
Stellar nucleosynthesis products in ejecta:
SNIa (= thermonuclear SN: $M_* < 8\ M_\odot$, accretion onto WD)





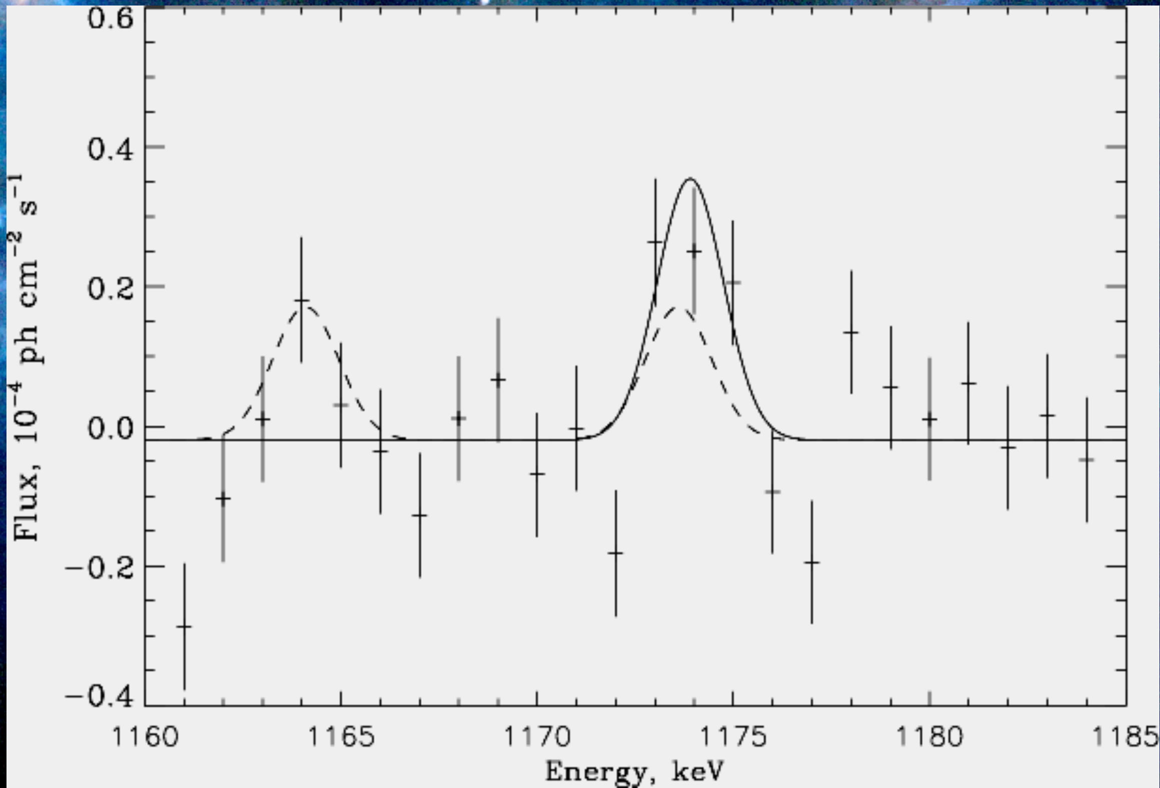
Townsley et al. 2003

Ubiquitous live ^{26}Al: The Milky Way @ 1.809 MeV
= Fresh (< 1 Myr) nucleosynthesis from massive stars (including SN)



CGRO Comptel (2001)

^{60}Fe (= SNII signature, τ ~ 1-3 Myr) in Cygnus X :
RHESSI detection confirmed by INTEGRAL



Φ_γ = 3.7 ± 1.1 x 10^{-5} cm^{-2} s^{-1}

INTEGRAL (ESA)
(Harris et al. 2005)

INTEGRAL γ-ray lines from the galactic plane…

- Interstellar ^{26}Al (also from CGRO) consistent (~ 2) with theoretical predictions for massive star yields
- Recent result: interstellar ^{60}Fe detected (RHESSI result, 2004, confirmed). Neutron-rich, unambiguous signature of « core-collapse SN » (observed as "SNII": $M_* > 8\ M_a$).
- Observed ^{60}Fe/^{26}Al line ratio = 0.11 ± 0.03, predicted ~ 0.2

  ⇒ 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

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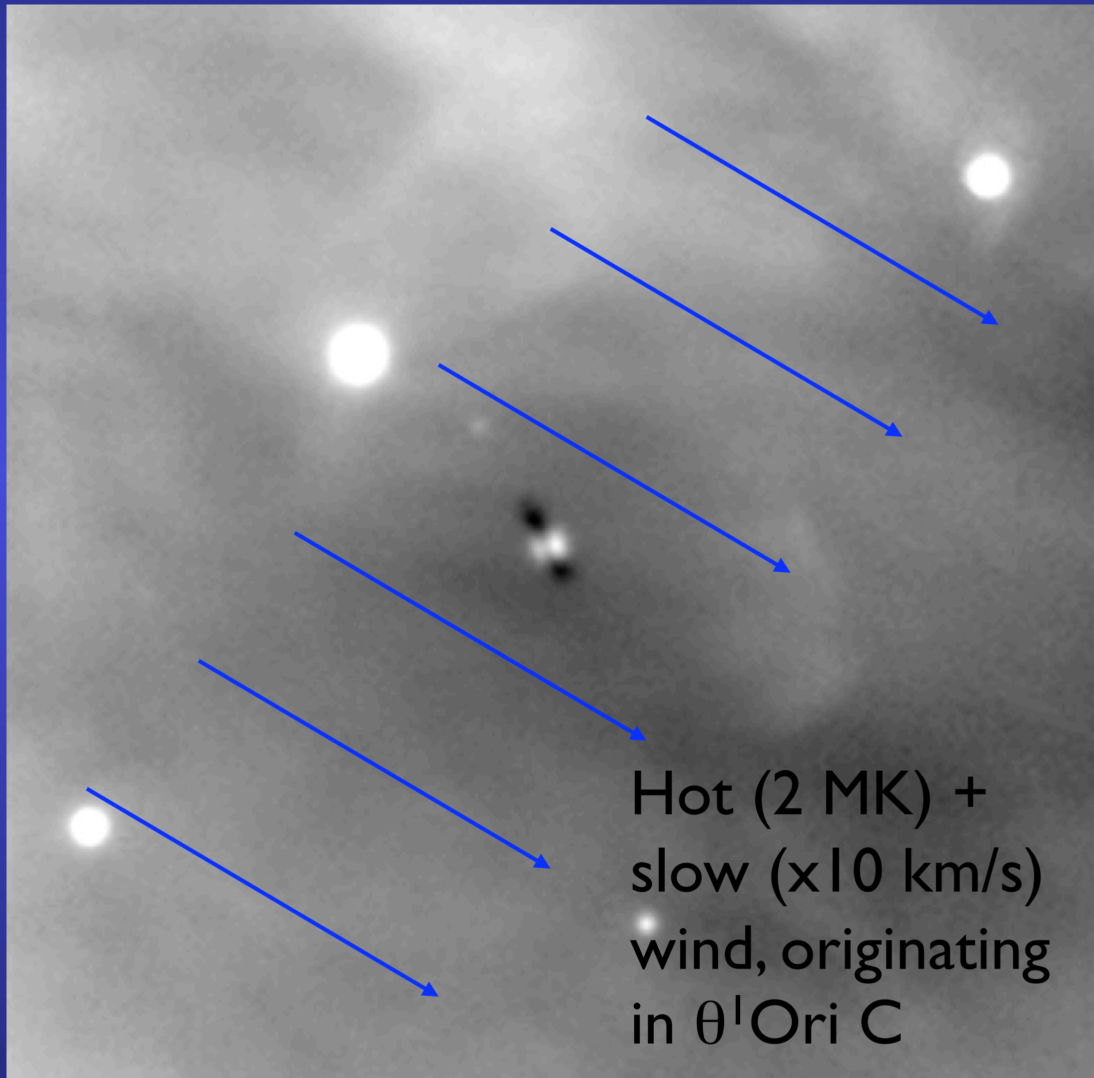
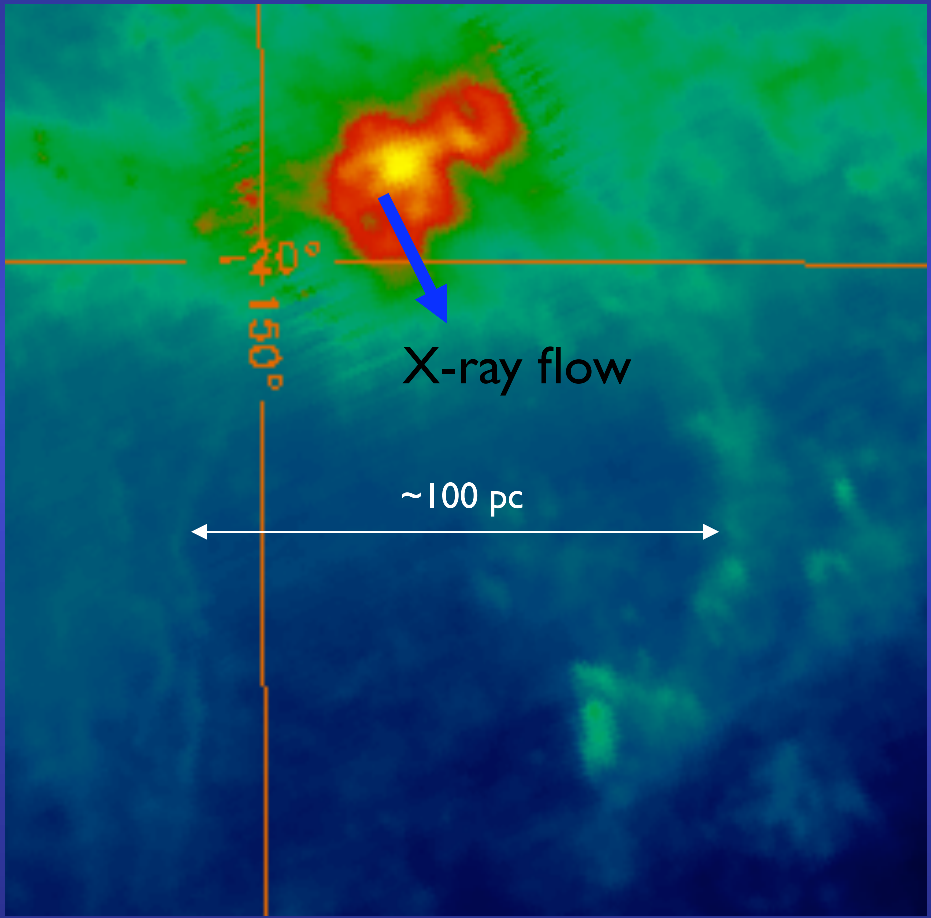
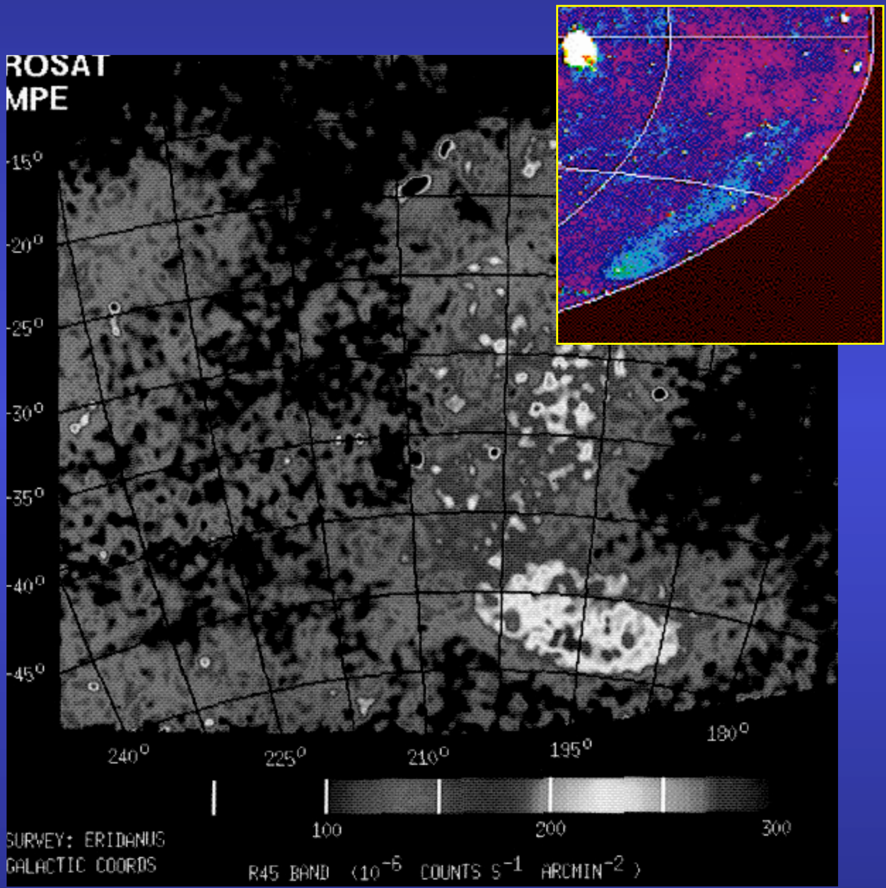
5. Superbubbles

A "hot bubble" bath for proplyds…



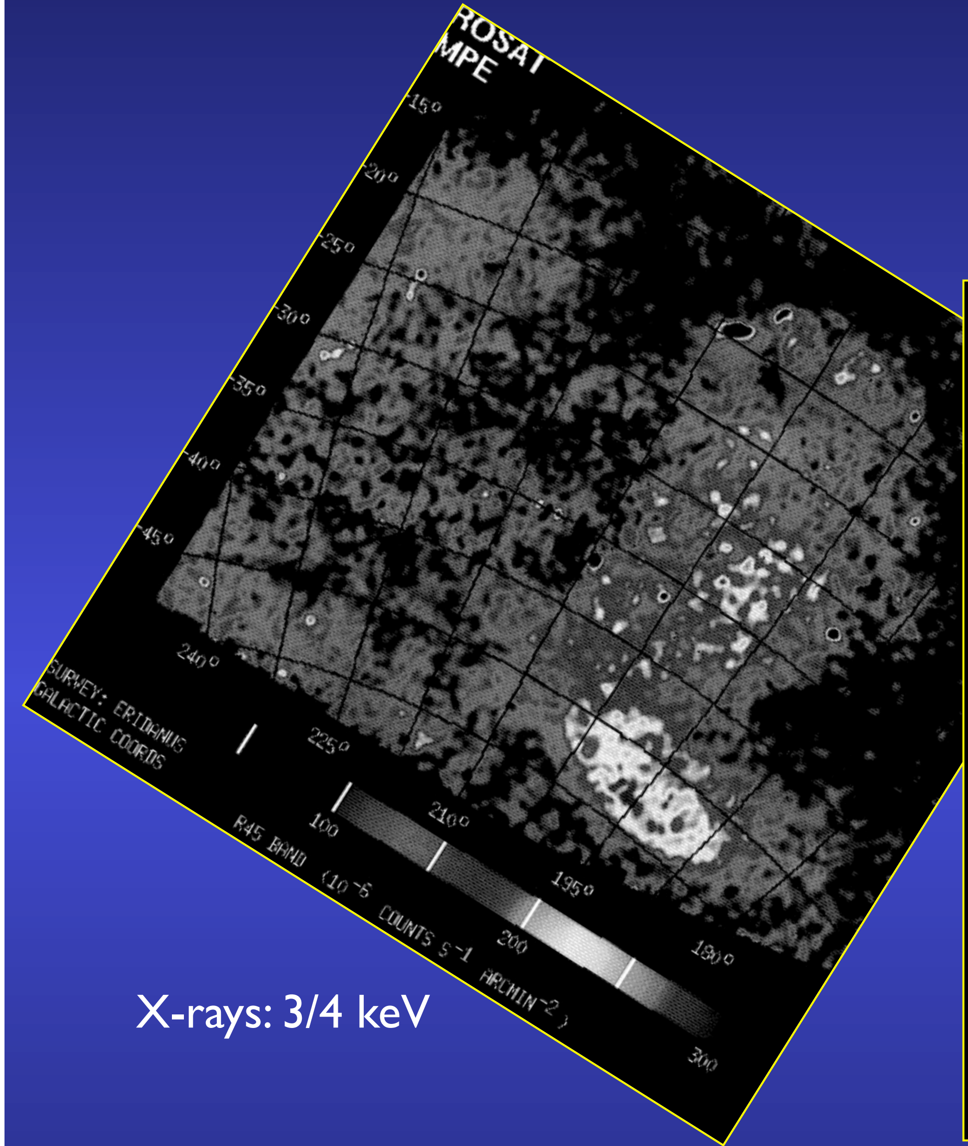
The "Eridanus superbubble": far, far away from the galactic plane…



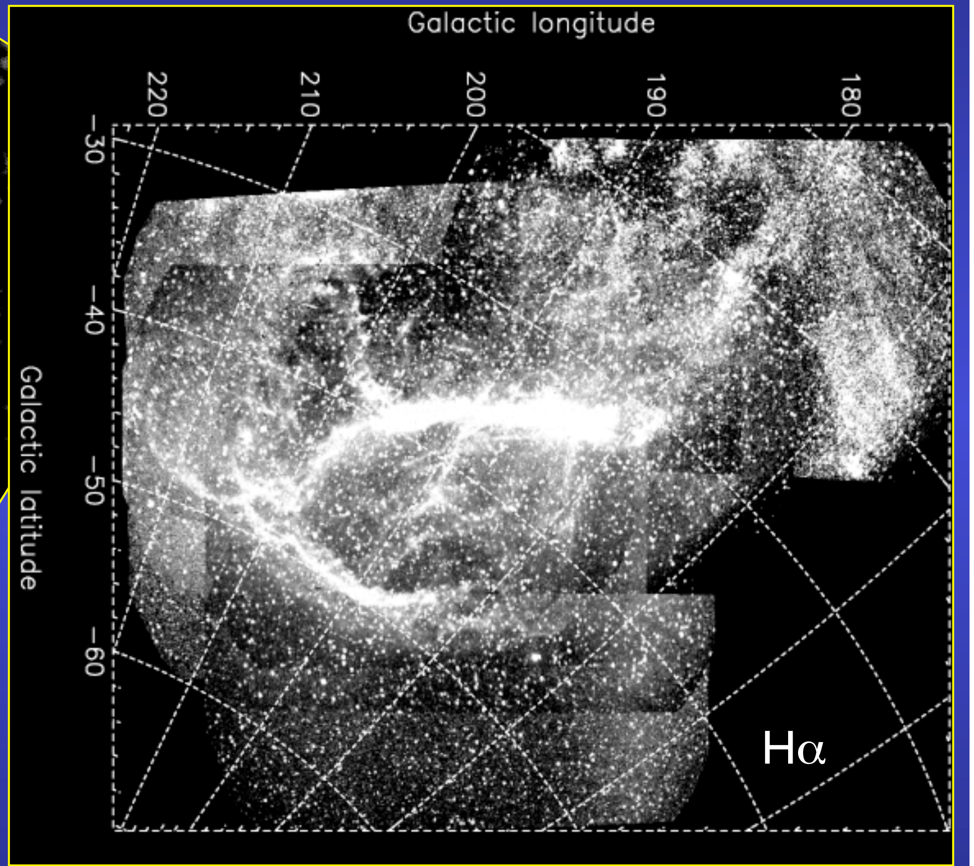


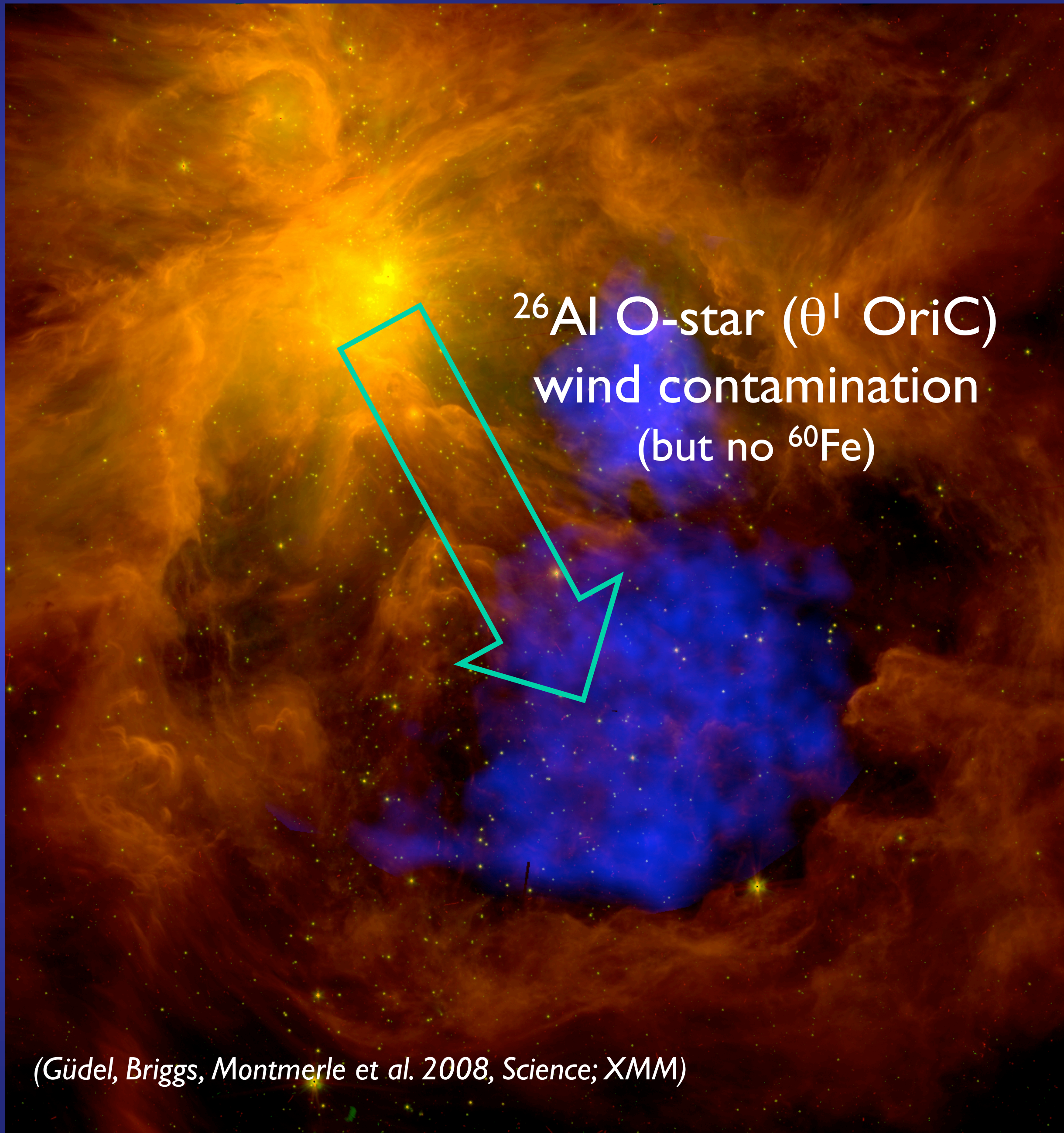
X-rays: 3/4 keV (Snowden et al. 1995)

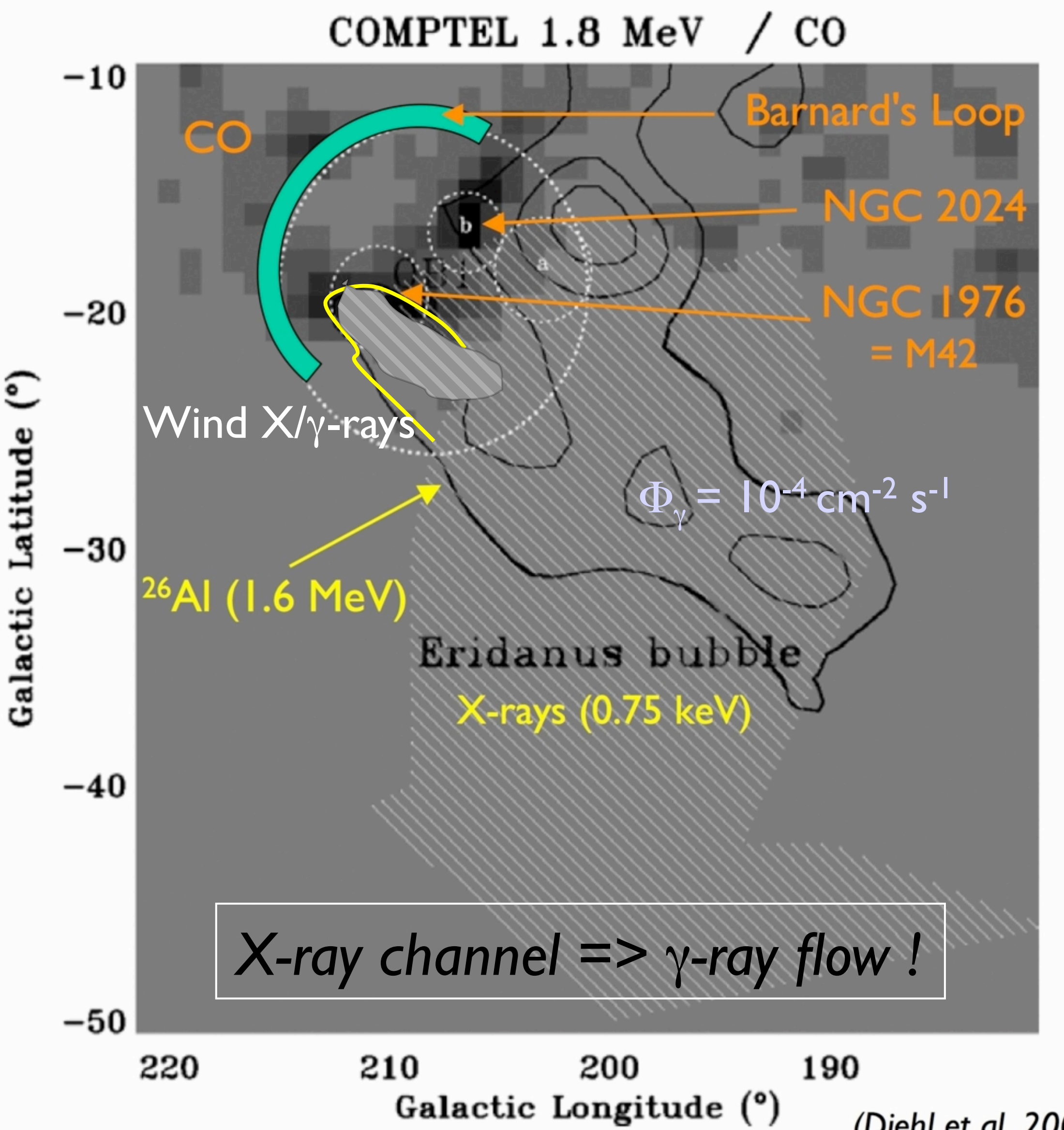
The Eridanus Superbubble



X-rays: 3/4 keV



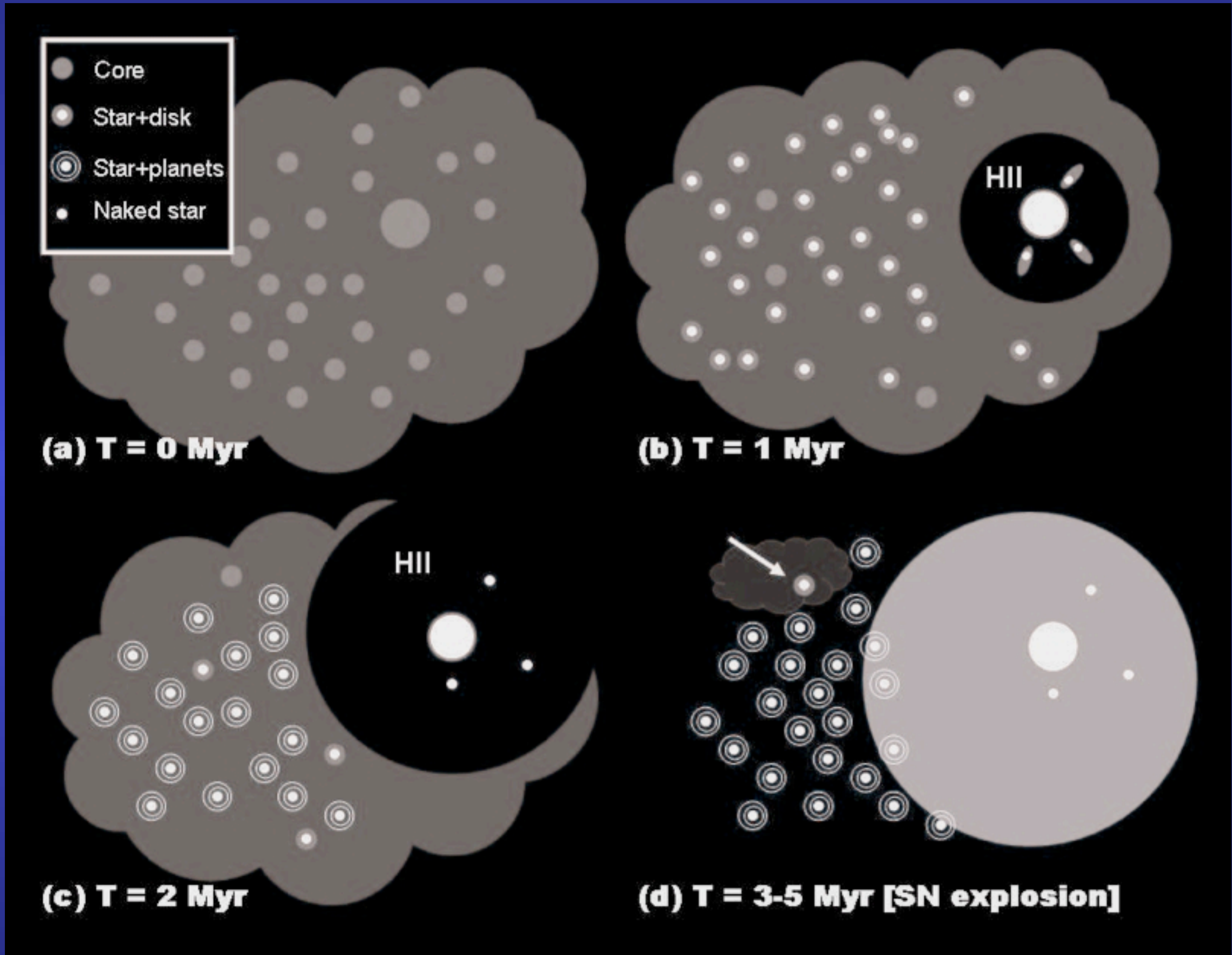

^{26}Al O-star (θ^1 OriC)
wind contamination
(but no ^{60}Fe)
(Güdel, Briggs, Montmerle et al. 2008, Science; XMM)

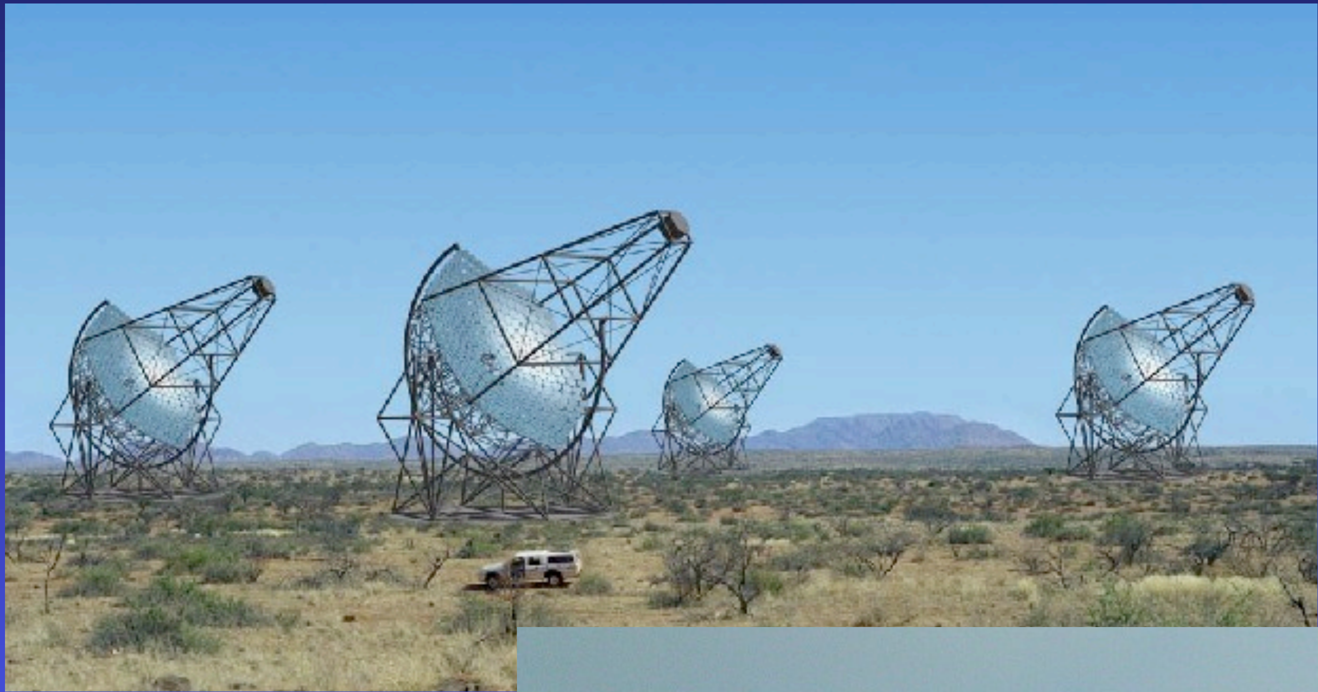


(Diehl et al. 2002)

6. Supernovae in SFRs

Early evolution of an "OB association"

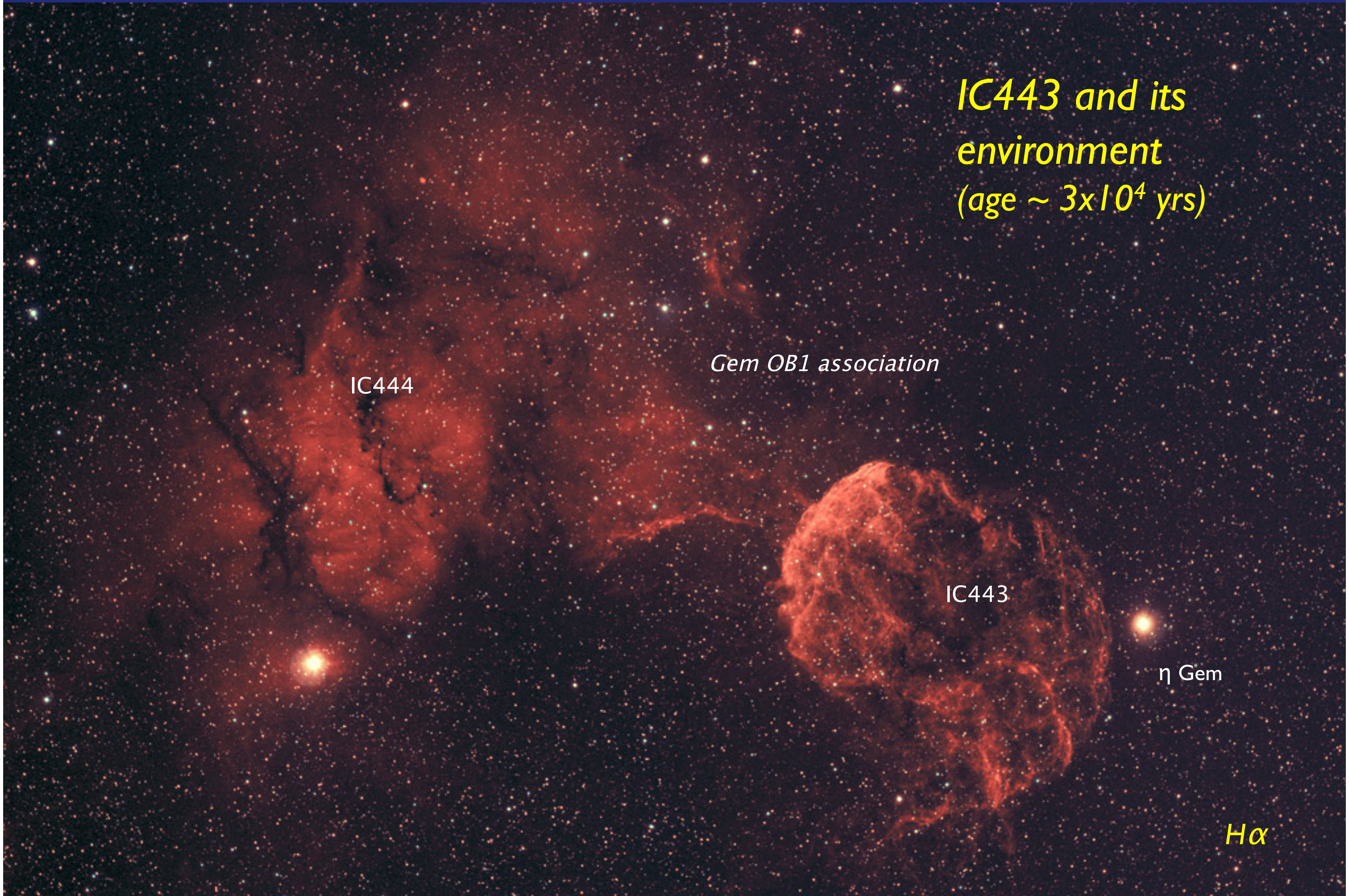




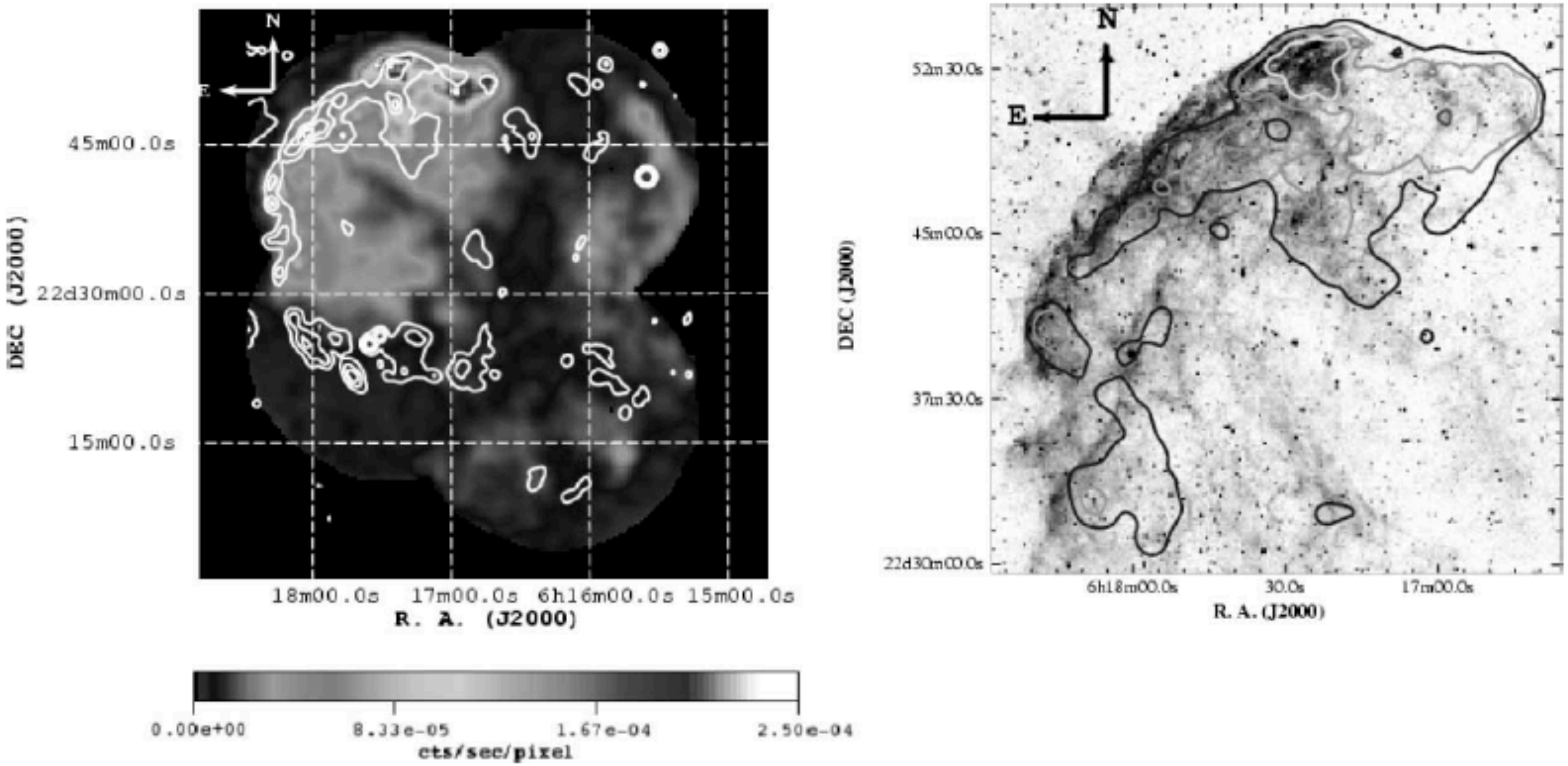
HESS
(Namibia)

Cerenkov
TeV telescopes
$\Delta\theta \sim$ 1-10'

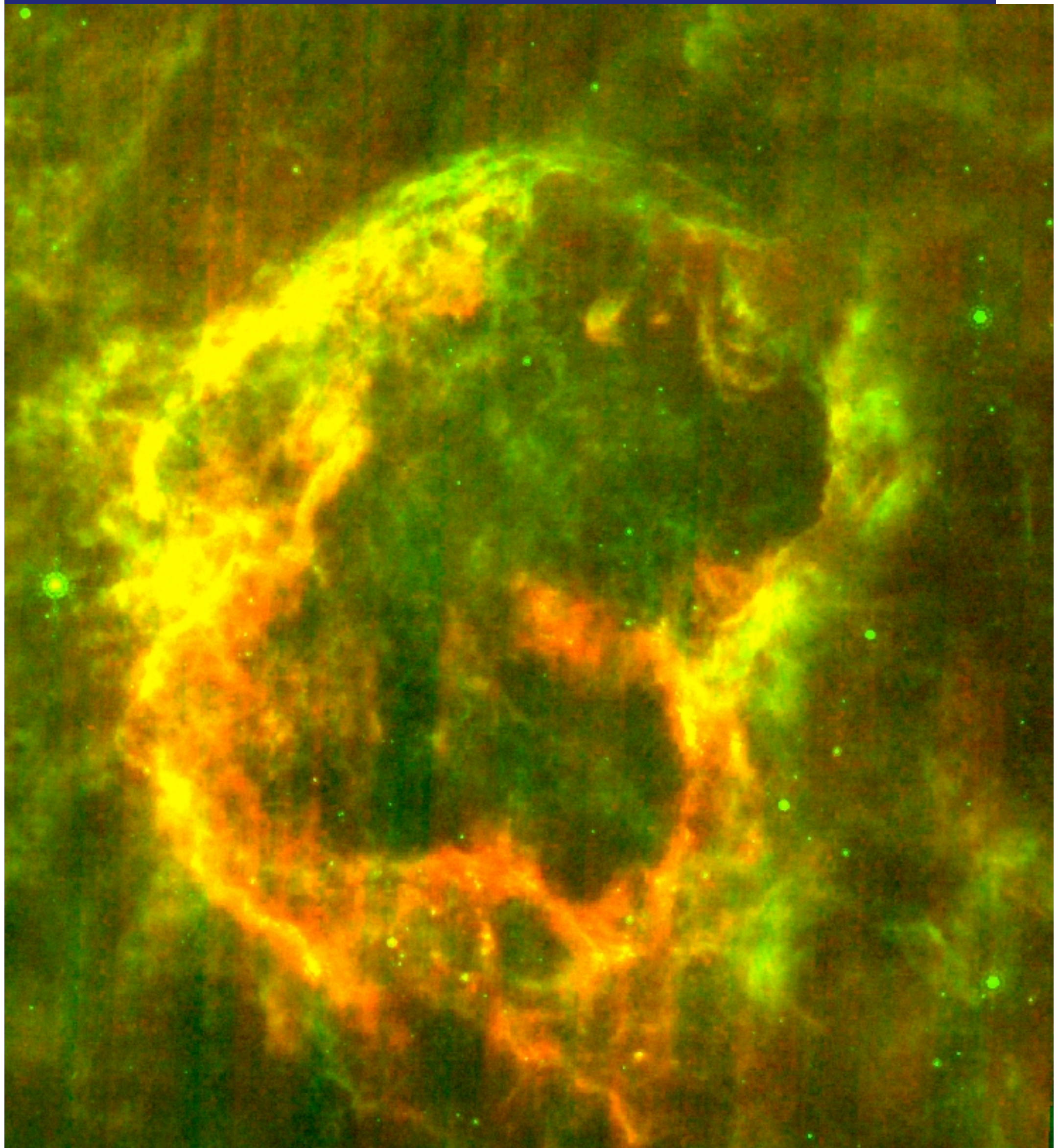
MAGIC
(Canary Isl.)


IC443 and its
environment
(age ~ 3x10⁴ yrs)
Gem OB1 association
IC444
IC443
η Gem
Hα

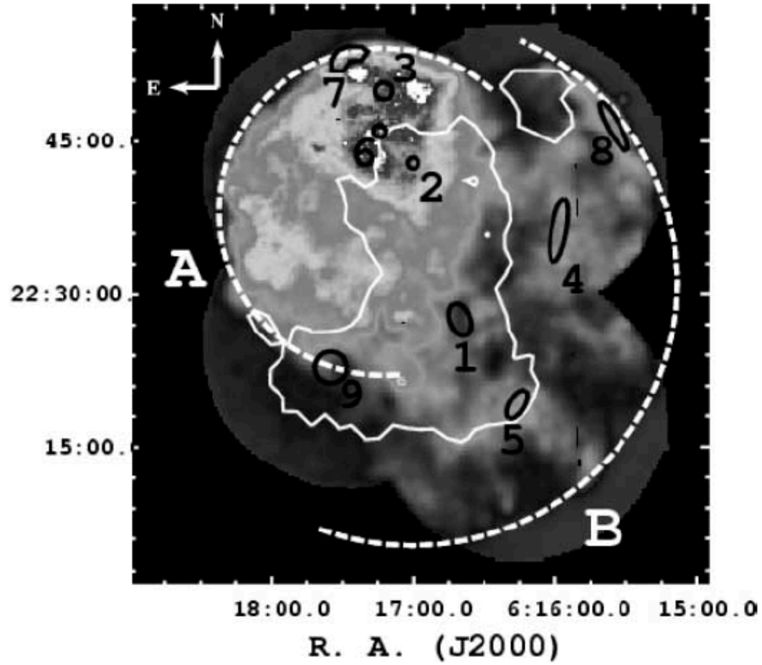
The XMM view of IC443

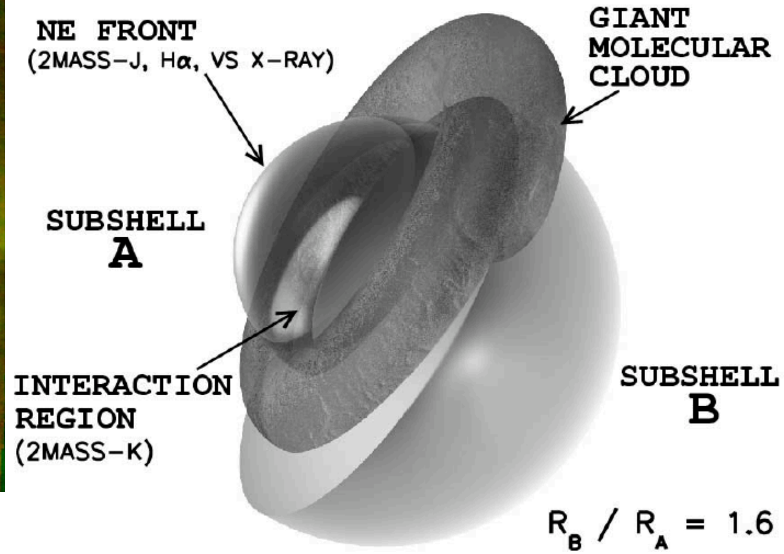


Troja et al. 2006



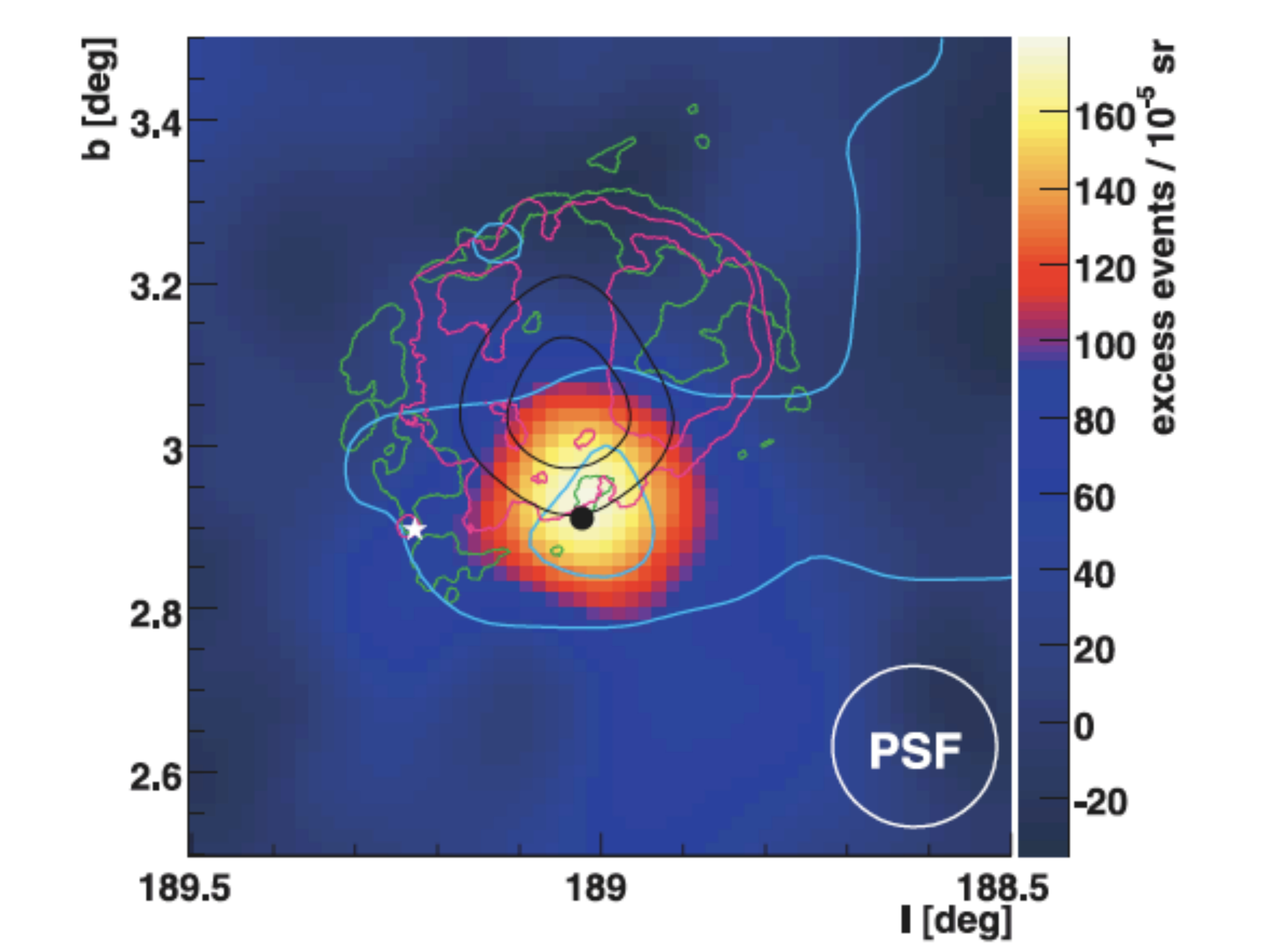
IC443: *Spitzer* (r70μm-g24μm)





Troja et al. 2006

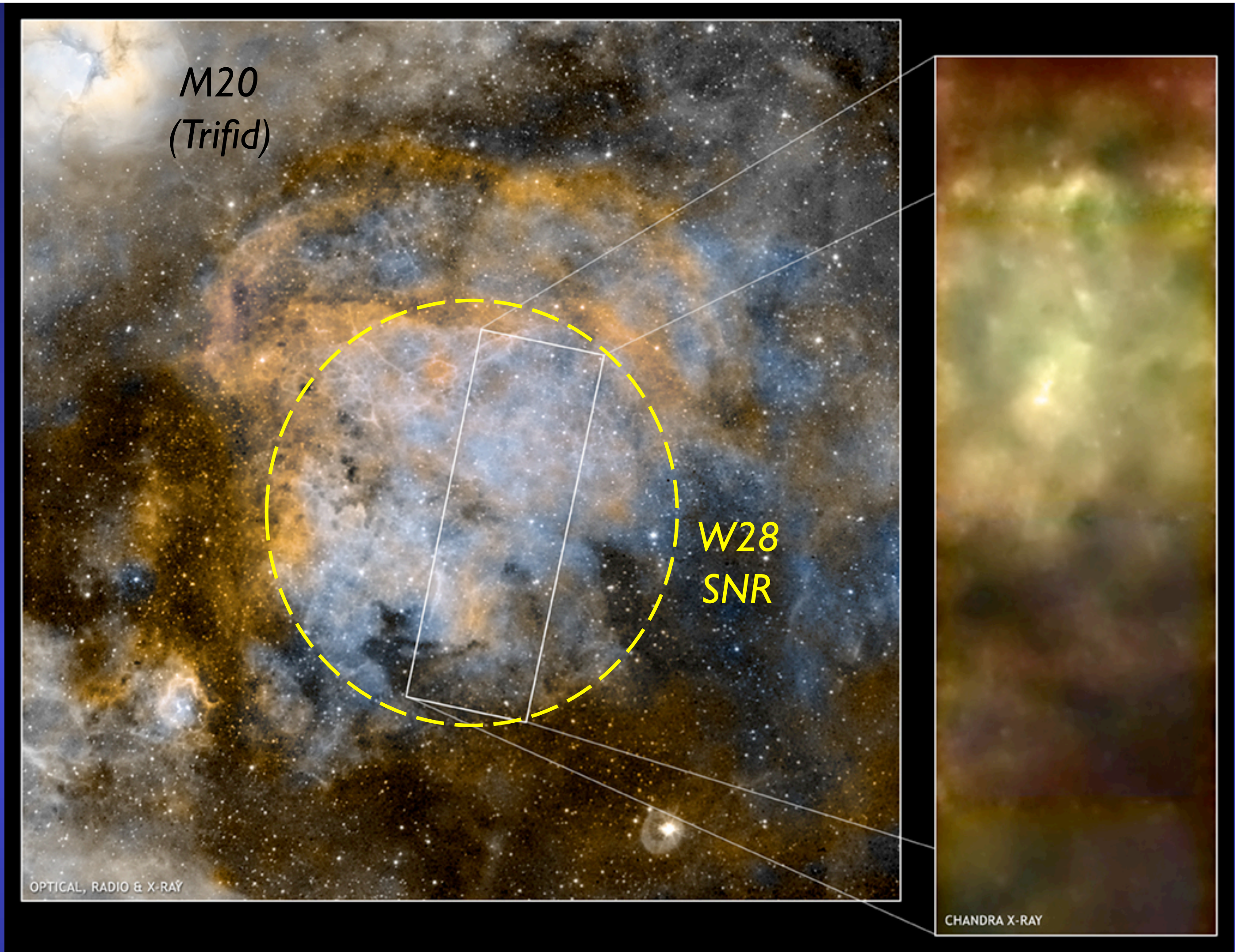
IC443: a GeV-TeV γ-ray source !



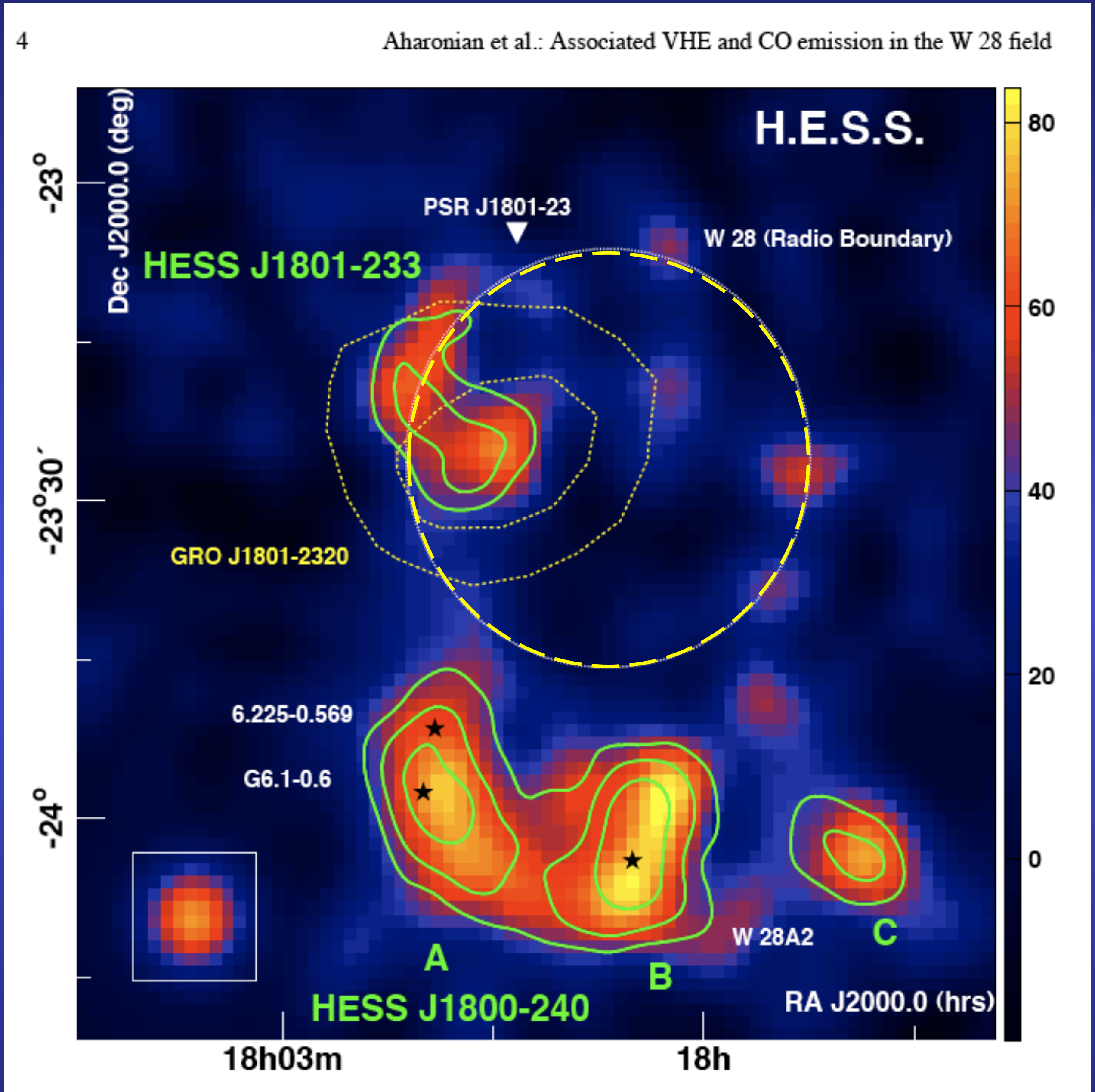
MAGIC (TeV): *Albert et al. 2007*

High-energy interactions of cosmic rays (E >1 GeV/n) with matter

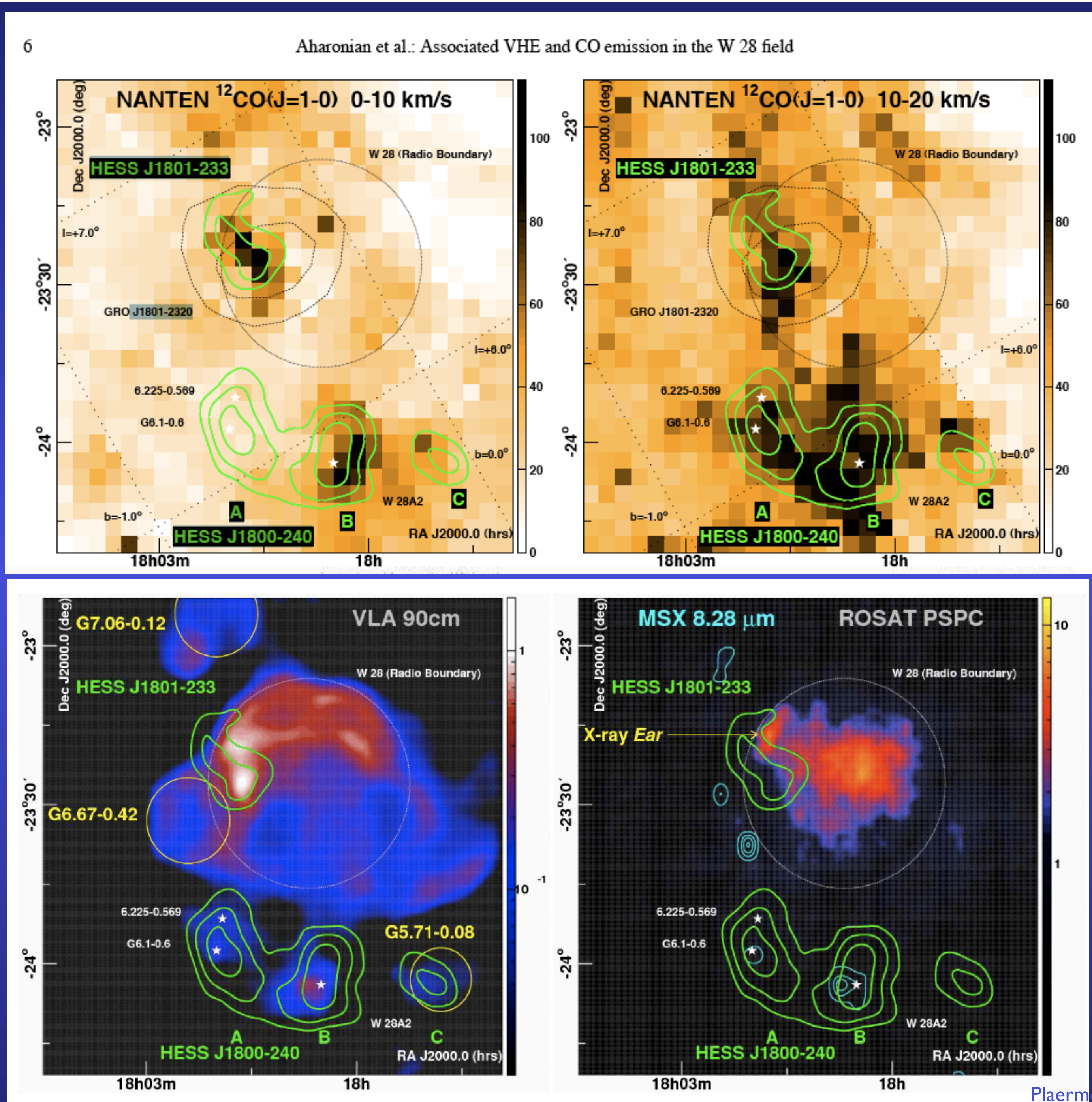
- *pp* collisions : “strong interaction”
  - $p + p \rightarrow p + p + \pi^+ + \pi^- + \pi^o$
  - $\pi^o \rightarrow 2\gamma$ (GeV $\rightarrow$ TeV)
- Predicted in the 60’s (Morrison 1958, Polack & Fazio 1963, Ginzburg & Sirovatskii 1964) as a probe of ISM
- => γ-ray maps (> 100 MeV) of the Milky Way
  - COS-B (~ 1985), CGRO/EGRET (~ 1995), GLAST (> 2008)
  - γ-ray emissivity $\propto$ GCR x CO ~ < fact.2-3, except for γ-ray *sources (enhanced CR density => local accelaration)*


M20
(Trifid)
W28
SNR
OPTICAL, RADIO & X-RAY
CHANDRA X-RAY

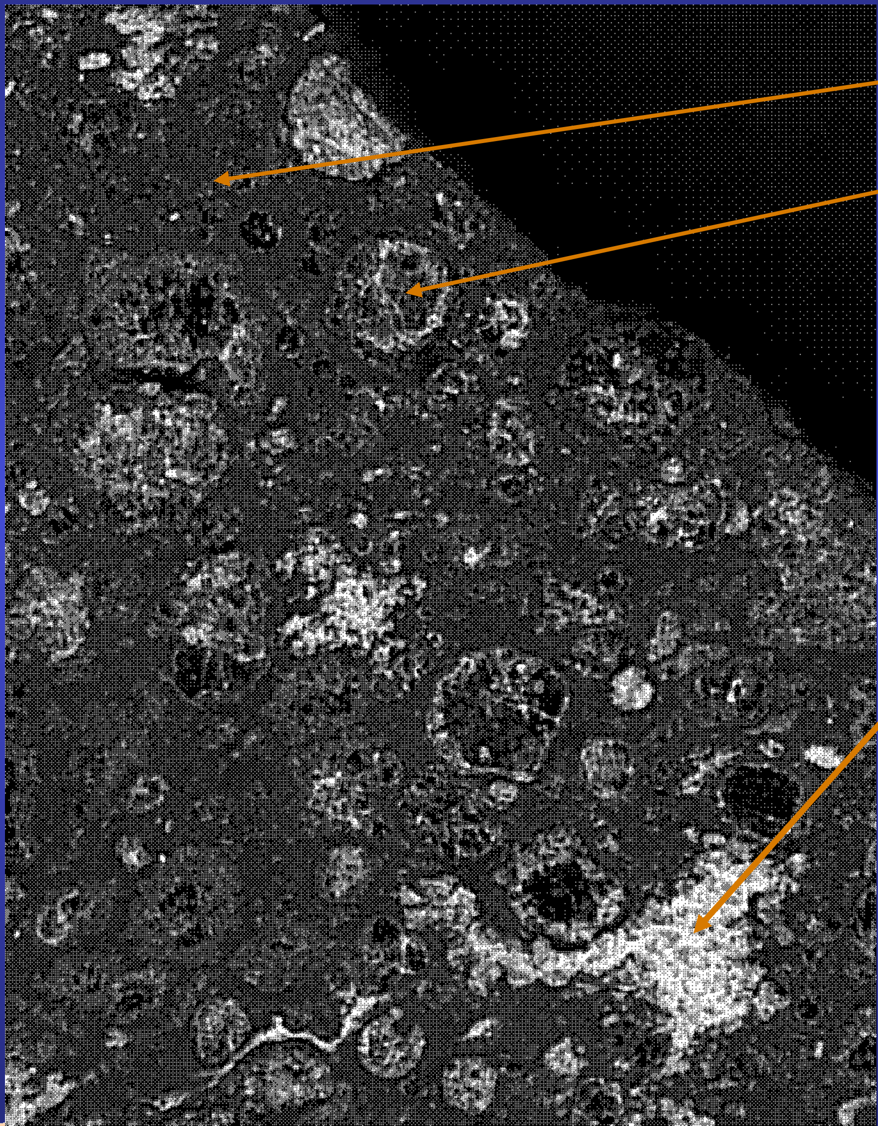
W28
SNR



Aharonian et al. 2009


NANTEN 12CO(J=1-0) 0-10 km/s
NANTEN 12CO(J=1-0) 10-20 km/s
HESS J1801-233
W 28 (Radio Boundary)
GRO J1801-2320
l=+7.0°
l=+6.0°
b=0.0°
b=-1.0°
6.225-0.569
G6.1-0.6
W 28A2
A
B
C
HESS J1800-240
RA J2000.0 (hrs)
Dec J2000.0 (deg)
18h03m
18h
-23°
-23°30'
-24°
VLA 90cm
G7.06-0.12
G6.67-0.42
G5.71-0.08
MSX 8.28 µm
ROSAT PSPC
X-ray Ear

The "extinct" radioactivities problem in meteorites



Matrix

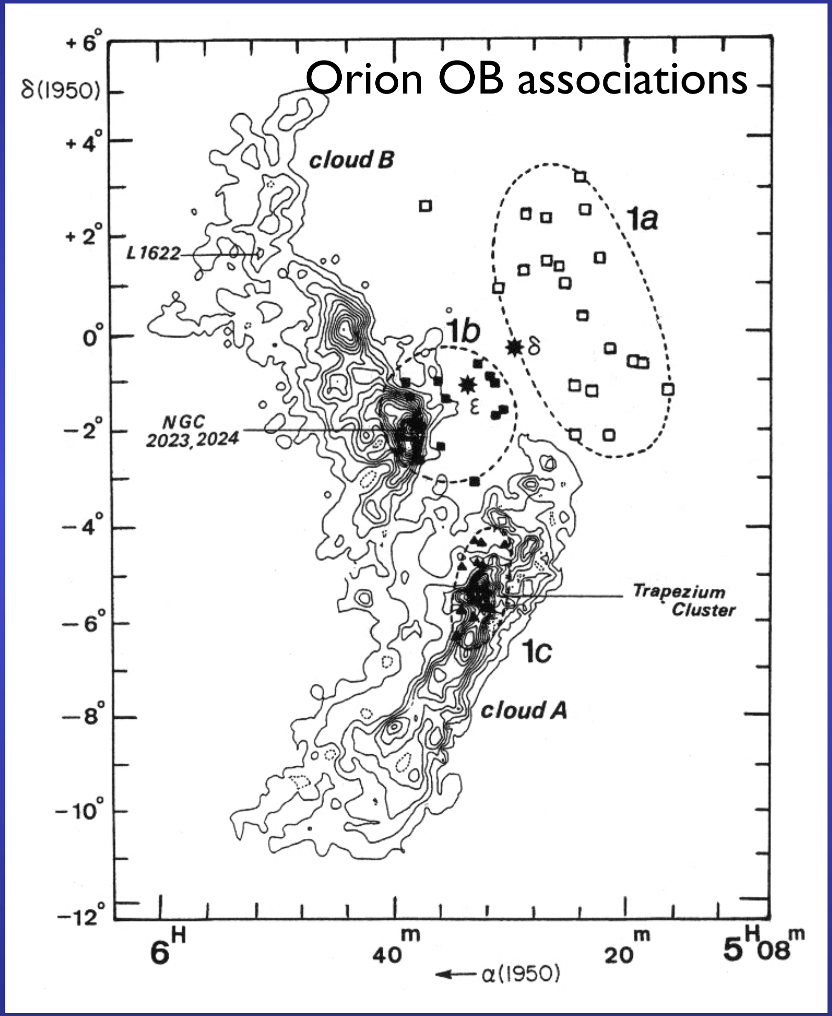
Chondritic grains

« Calcium-Aluminium Inclusions» (CAIs):
= radioactive disintegration of isotopes
^{7}Be ^{10}Be ^{26}Al ^{36}Cl ^{41}Ca ^{53}Mn ^{60}Fe
("extinct", short-lived radioactivities)

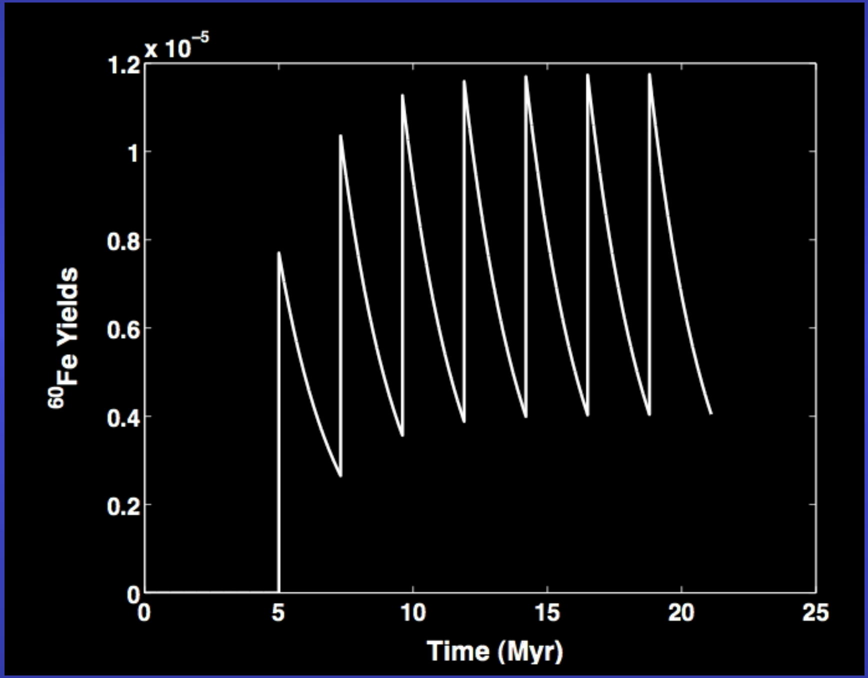
Gounelle, Chaussidon, Shu, et coll.

Allende (Mexico, 1969; ~ 2 tons !)

A galactic "background" of ^{60}Fe ?

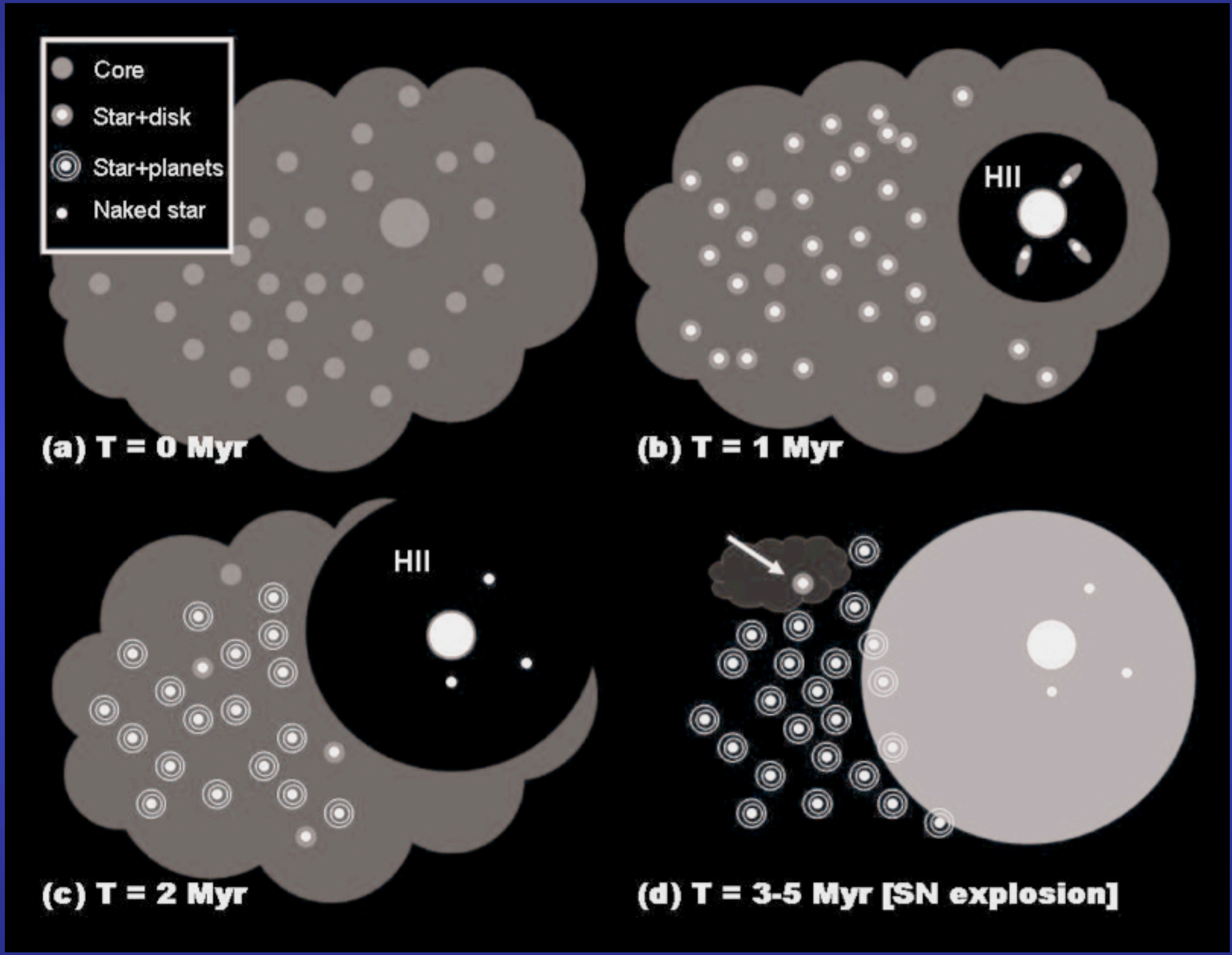


Blaauw 1991

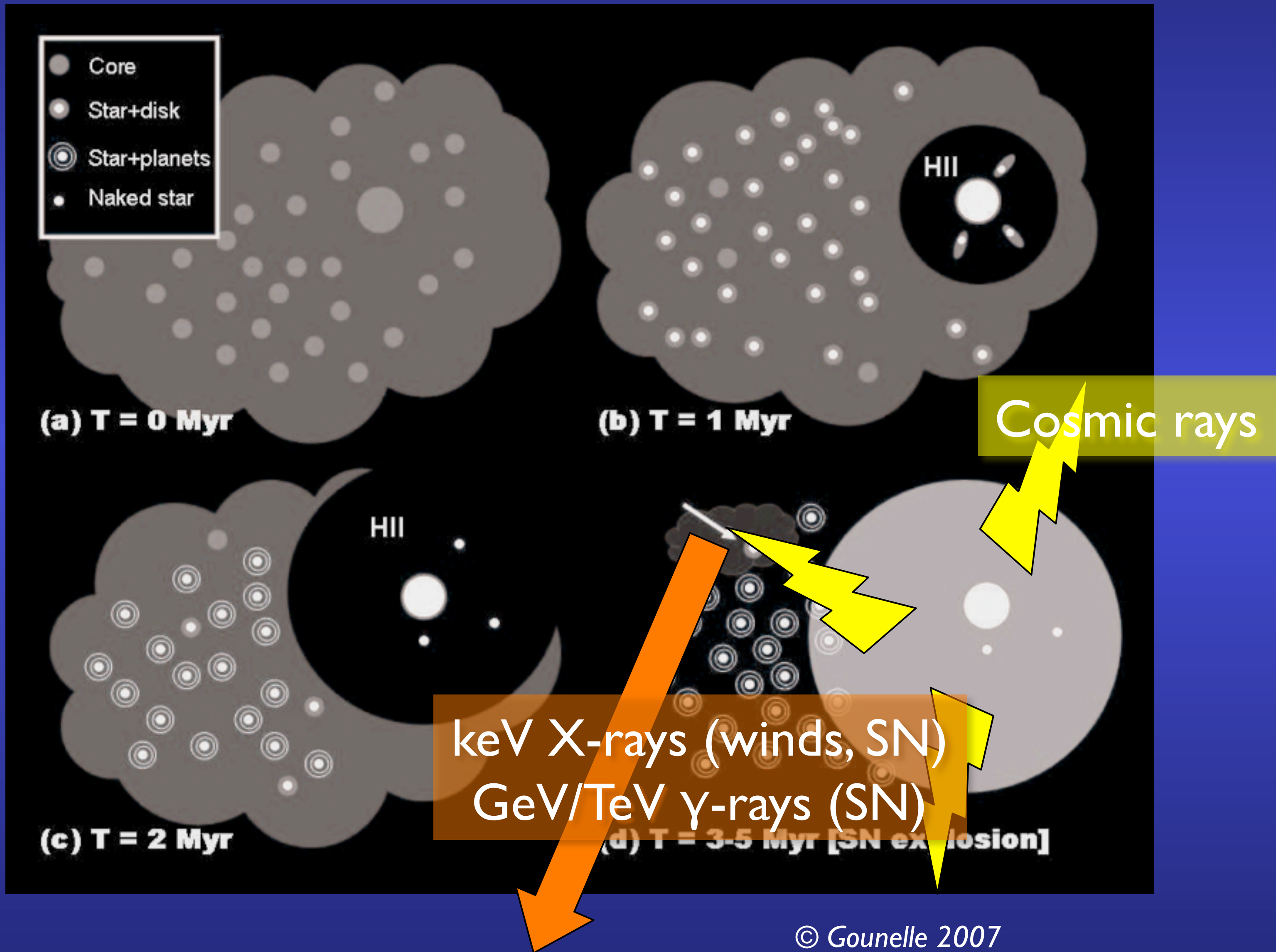


Gounelle et al. 2008

Early evolution of an "OB association": the "cradle of the Sun"?



Early evolution of an "OB association": the "cradle of the Sun"?



© Gounelle 2007

7. Conclusions

- Diffuse X-ray emission in massive SFRs is now well established
- Result of high-speed shocks associated with massive stars over a few Myr:
  - Winds (continuous)
  - Supernovae (“spikes”)
- The hot plasma flows into the ISM, creating “superbubbles”
- Apart from young SNRs, impossible (so far) to find nucleosynthetic products in spectra of diffuse X-rays
- Evidence for ongoing nucleosynthesis by γ-ray lines
- May have implications for the “cradle of the Sun” (was there a supernova in the vicinity of the young solar system ?)