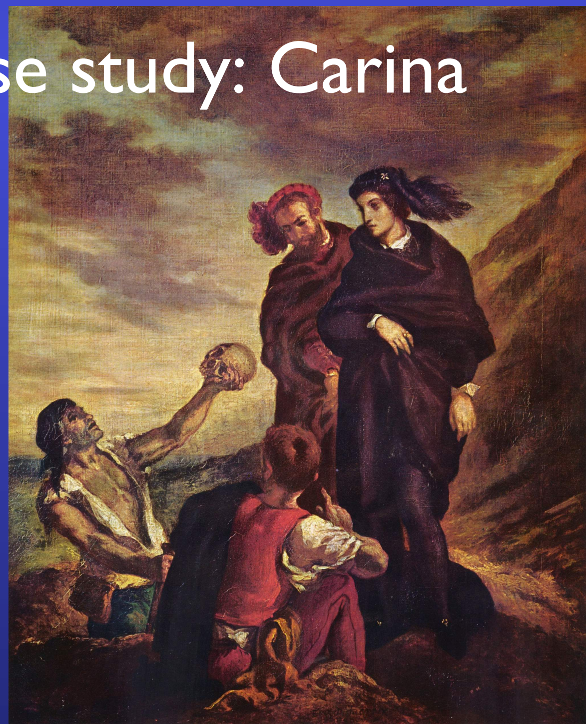

Gamma-rays from star-forming regions:
to be or not to be...
(work-in-progress...)
Thierry Montmerle
Laboratoire d'Astrophysique de Grenoble, France
LAOG
Montpellier PCHE (7-9/9/09) 1

Outline

- 1. Background: γ-rays from star-forming regions
- 2. TeV vs. GeV sources
- 3. *To be:* "Positive" case studies: IC443, W28
- 4. *Not to be:* "Negative" case study: Carina
- 5. Making sense ?
- 6. Concluding remarks



LAOG

1. Background: γ-rays from star-forming regions

Introduction and historical context

- Early theorectical predictions of *pp* $\pi°$-decay emission from the Galaxy (in physics papers…: Pollack & Fazio 1963, Hayakawa et al. 1964, Ginzburg & Syrovatskii 1964, etc.):

  => *search for the origin of cosmic rays*

- Discovery of > MeV [balloon] + TeV [Čerenkov] pulsed emission from the Crab Pulsar (Albats et al. 1972; Grindlay 1972): power-law spectrum from radio (=> synchrotron emission)
- Early hints of 10-100 MeV γ-ray sources in the galactic plane from balloon flights: Cygnus, galactic center (~ 1970)
- Breakthroughs with the first γ-ray satellites:
  - [OSO-3, NASA (1967-1968), E_γ > 50 MeV]
  - SAS-2, NASA (1972-1973), E_γ = 20 MeV - 1 GeV
  - COS-B, ESA (1975-1982), E_γ = 30 MeV - 5 GeV

LAOG Laboratoire d'AstroPhysique de Grenoble

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

- *pp* collisions : "strong interaction"
  - $p + p \rightarrow p + p + n(\pi^+ + \pi^- + \pi^\circ)$ [*n* increasing with E_p]
  - $\pi^\circ \rightarrow 2\gamma$ (GeV $\rightarrow$ TeV)
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$ followed by $\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu}$
  - $\pi^- \rightarrow \mu^- + \overline{\nu_\mu}$ followed by $\mu^- \rightarrow e^- + \overline{\nu_e} + \nu_\mu$

- => γ-ray maps (> 100 MeV) of the Milky Way
  - COS-B (~ 1985), CGRO/EGRET (~ 1995), GLAST/Fermi (> 2008)
  - γ-ray emissivity ∝ GCR x CO ~ < fact.2-3, except for γ-ray *sources (enhanced CR density => local accelaration)*

γ-ray emissivity from
pp -> π° interactions

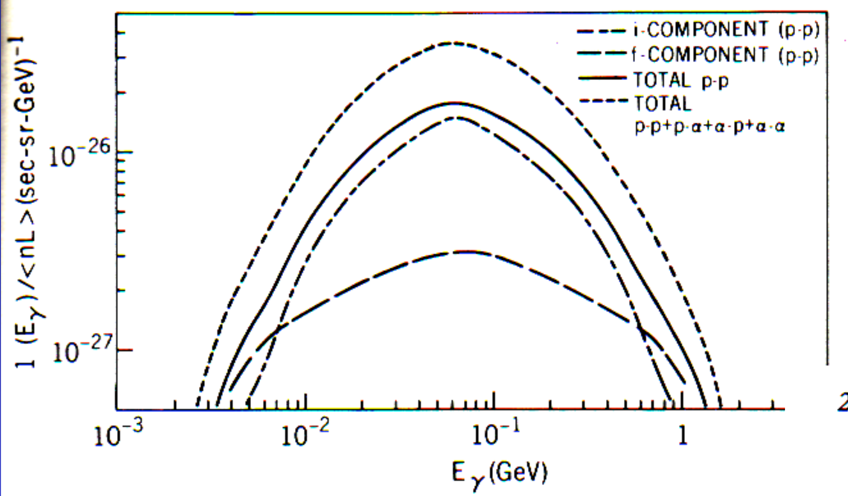


Figure IX.A-3. The calculated differential production spectrum of γ-
produced in cosmic-ray interactions in the galaxy based on the "isoba
plus-fireball (f)" model of Stecker (1970).

222 THEORY

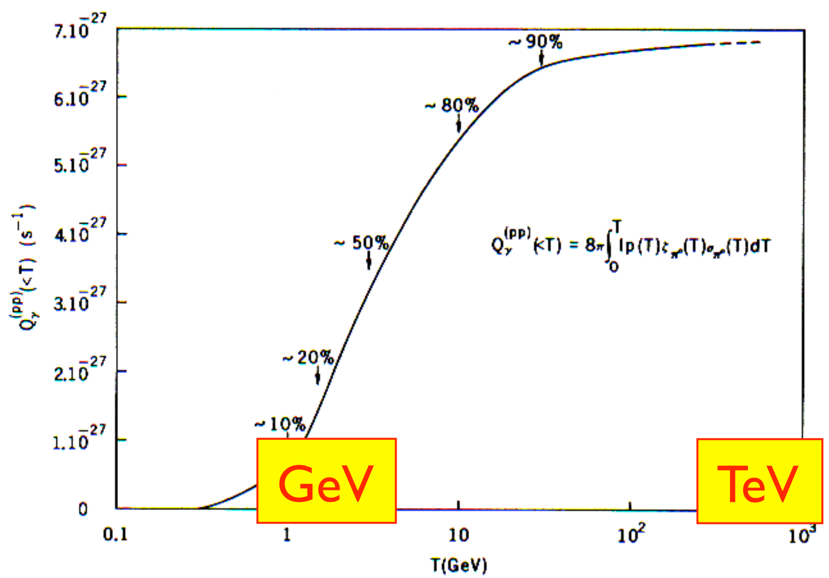
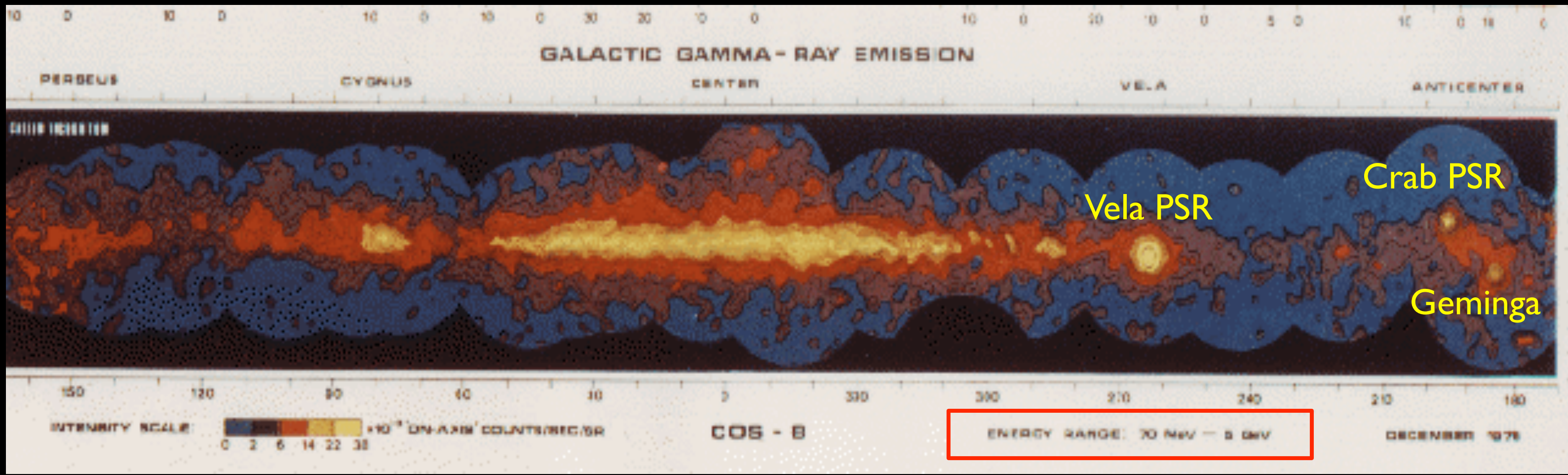


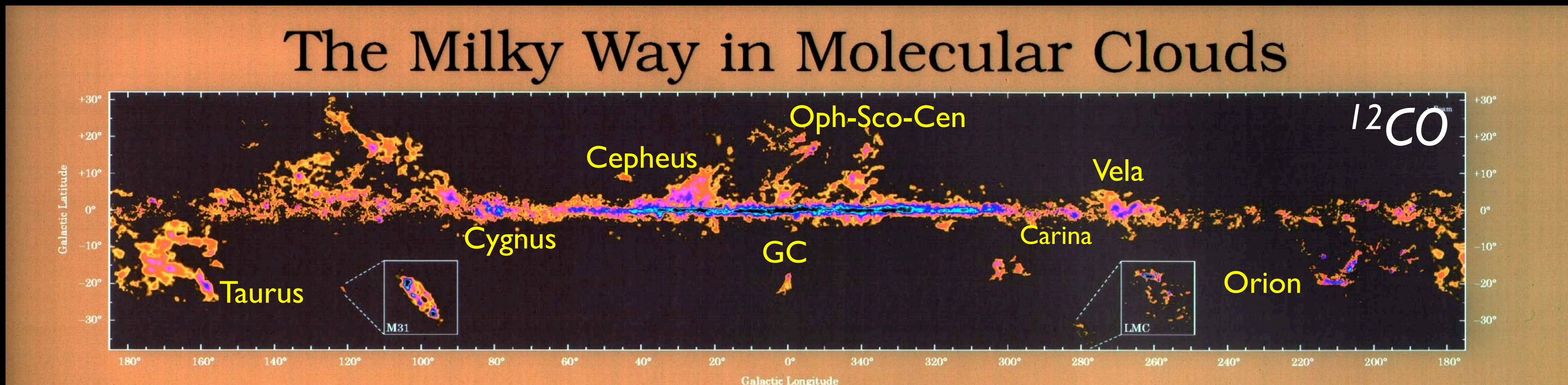
Figure IX.A-8. Integral γ-ray production function from the decay of neutral pions produced in p-p interactions.

(Stecker 1973)

LAOG
Laboratoire d'AstroPhysique de Grenoble



COS-B: Bloemen et al. 1982



Dame et al. 2002

What is a (sub-GeV) γ-ray source ?

- Background:
  - Instrumental (anticoincidence efficiency)
  - *Galactic:* high-energy GCR (*p* + *e*) + ISM (H_2)+ UV-IR
  - => low contrast for source detection
- ISM distribution: ^{12}CO survey (resol. ½°, 1987; resol. ⅛°, 2001)
- => galactic "source" = local "excess" ("hot spot")

  = *modeled* diffuse emission – observed emission
  - Depends on diffuse emission model: [CR *p*+e] + [matter+photons]
    - *p* (π ° decay) + e (bremsstrahlung + inverse Compton)
  - Source list revisions (Last: EGR catalog: Casandjian & Grenier 2008)

The SNOB hypothesis

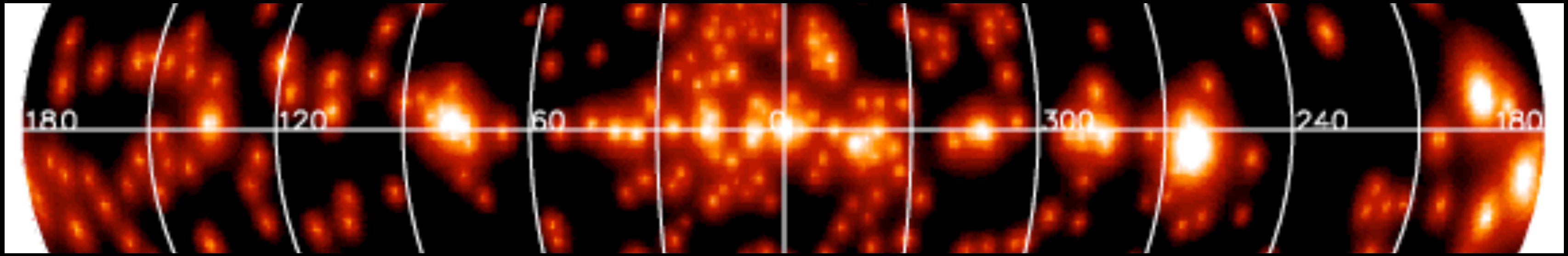
- First COS-B catalog (Hermsen et al. 1977): 13 γ-ray sources over 1/3 of the galactic disk
  - 2 pulsars (Crab + Vela)
  - 11 remaining unidentified sources: 5-6 coincide with regions of massive star formation (HII regions, and/or OB associations) associated with a shell-like supernova remnant (SNII) (Montmerle 1979, Cassé & Paul 1981, Montmerle & Cesarsky 1983…)
  - => SN+OB… = "SNOBs"
- Proposed scenario: two-step process:
  - Using CR diffusive shock acceleration models
  - *Injection* of low-energy CR by active low-mass stars in an association
  - *Acceleration* by a SN shock wave (from massive stars in *same* association)

- SN shock acceleration later generalized to acceleration at *fast stellar wind* shocks ("SWOBs") = long-lived (Myr) "inverted SN"
- Molecular cloud mass (~ 10^{4-5} $M_\odot$) + distance (~ few kpc)
  => local CR flux density > 10-100x GCR
- CR *confinement* necessary to interact with a large mass: ionized, magnetized gas (HII region; 10-20 μG, Heiles et al. 1981); possible also in turbulent, magnetized molecular clouds
- Examples: W28, IC443, RCW86… (e.g., Torres et al. 2003)

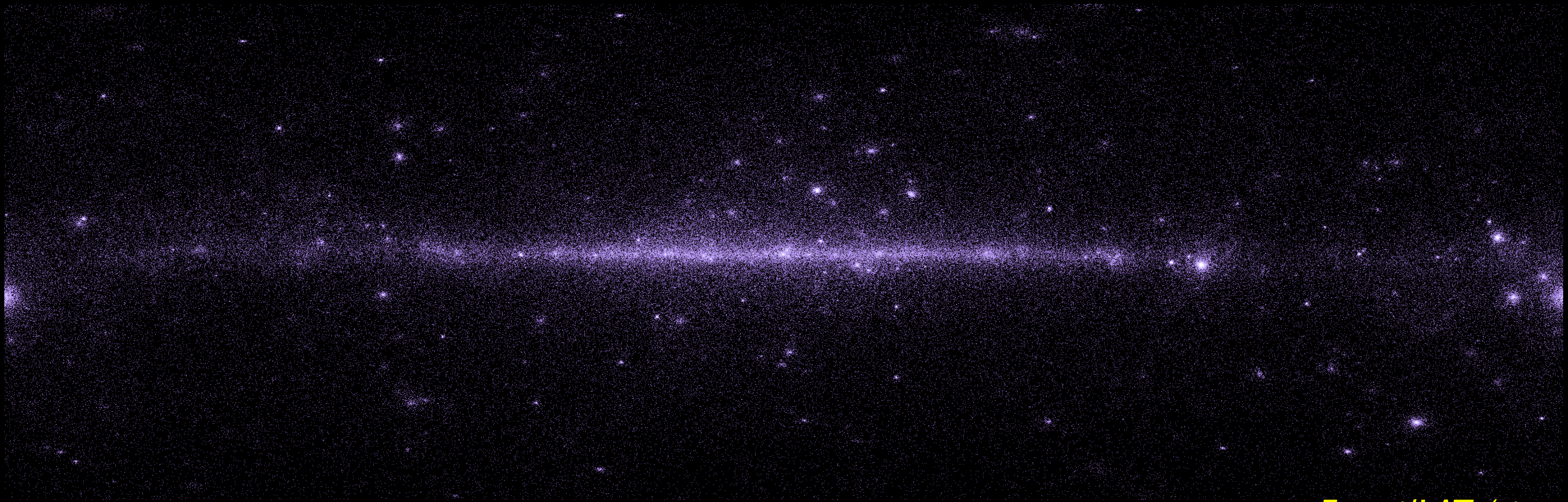
2. TeV vs. GeV sources

- Post-COS-B, GeV sources: *Compton* GRO/EGRET
- All-sky survey, FOV radius = 25°, $\Delta\theta$ = 5-30'
  - Last revision (# 4: 9 yrs of data): Casandjian & Grenier 2008
  - 271 sources (3EG) → 188 (EGR) (-107+30)
    - Improved corrections for diffuse background and local features
    - Many ex-sources are "local" matter features (normal GCR)
  - SNRs in galactic plane confirmed as class of GeV γ-ray sources (Torres et al. 2003)
- Anxiously waiting for *Fermi* (ex-GLAST) results !
  - Must wait for improved estimates of galactic GeV background in localized regions (e.g., star-forming regions <–> molecular clouds)
  - see discussion on X_{CO} in "passive" clouds *(L. Tibaldo)*

LAOG
Laboratoire d'AstroPhysique de Grenoble

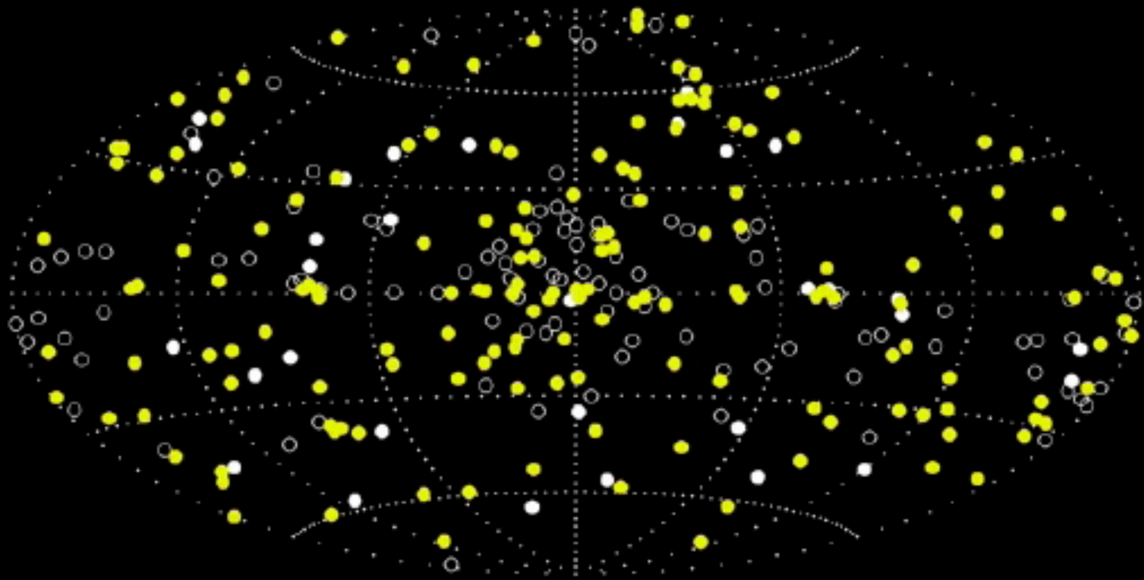


CGRO/EGRET

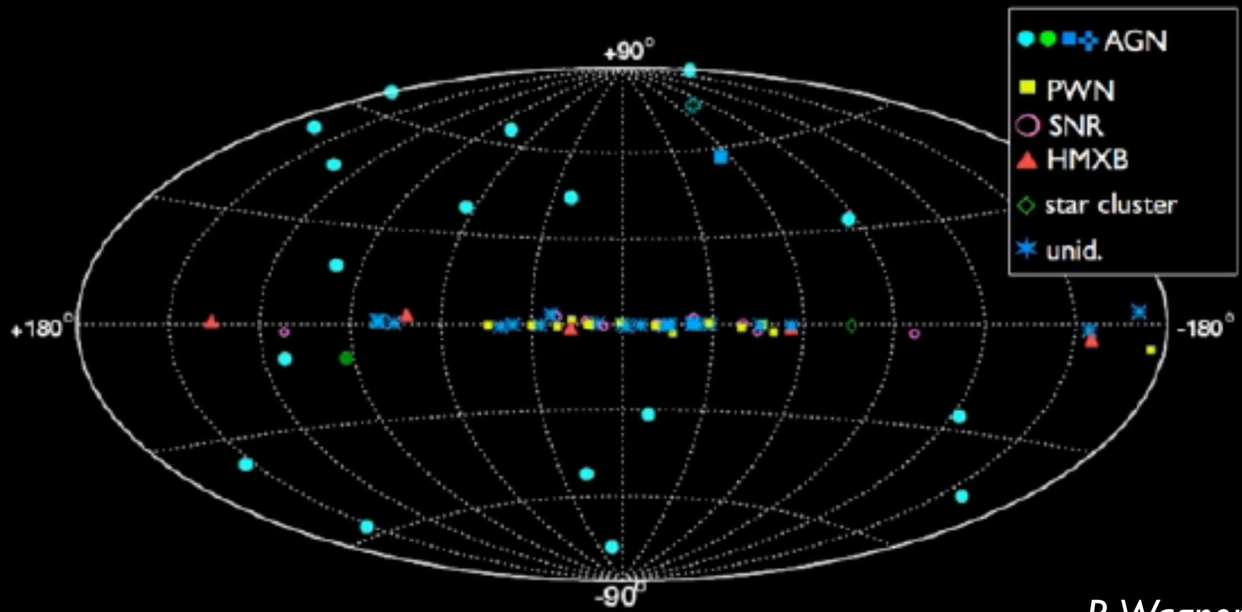


Fermi/LAT (simul.)

- Breakthrough with the advent (> 2000) of *high-resolution ground-based Čerenkov telescopes* and arrays (TeV energies: Cangaroo, VERITAS, MAGIC, HESS…): $\Delta\theta \sim 0.1°$
  - Also: TeV γ-rays = 100% of $\pi°$ emissivity (10% @ 1 GeV)
- Follows decades of difficult technological progress (detectors, mirrors, understanding EAS, etc.): > 1970
- => Evidence for *extended* sources
  - Look for counterparts at other wavelengths
  - No problem with galactic TeV γ-ray diffuse background
  - Galactic plane survey (HESS)



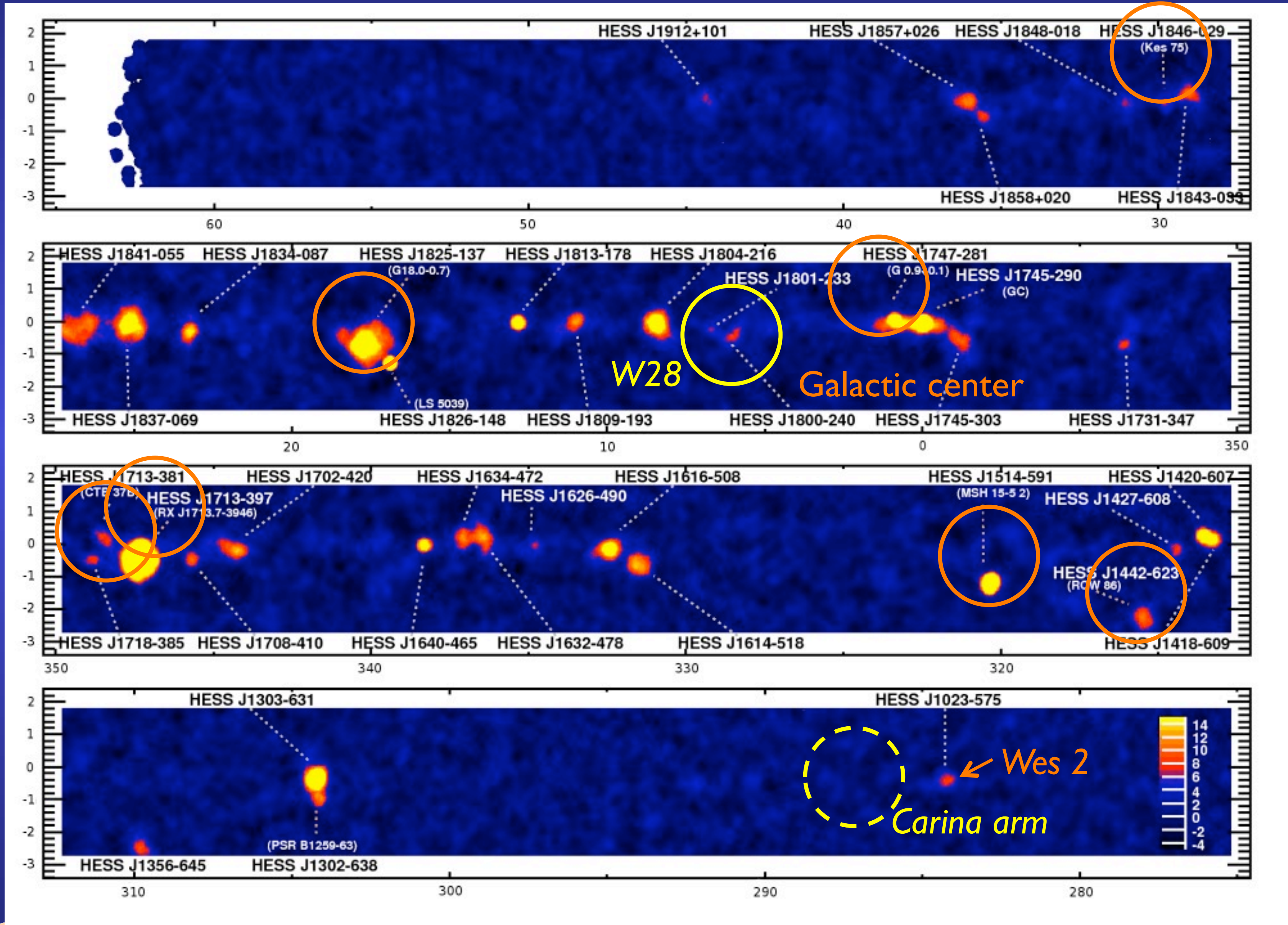
3EG



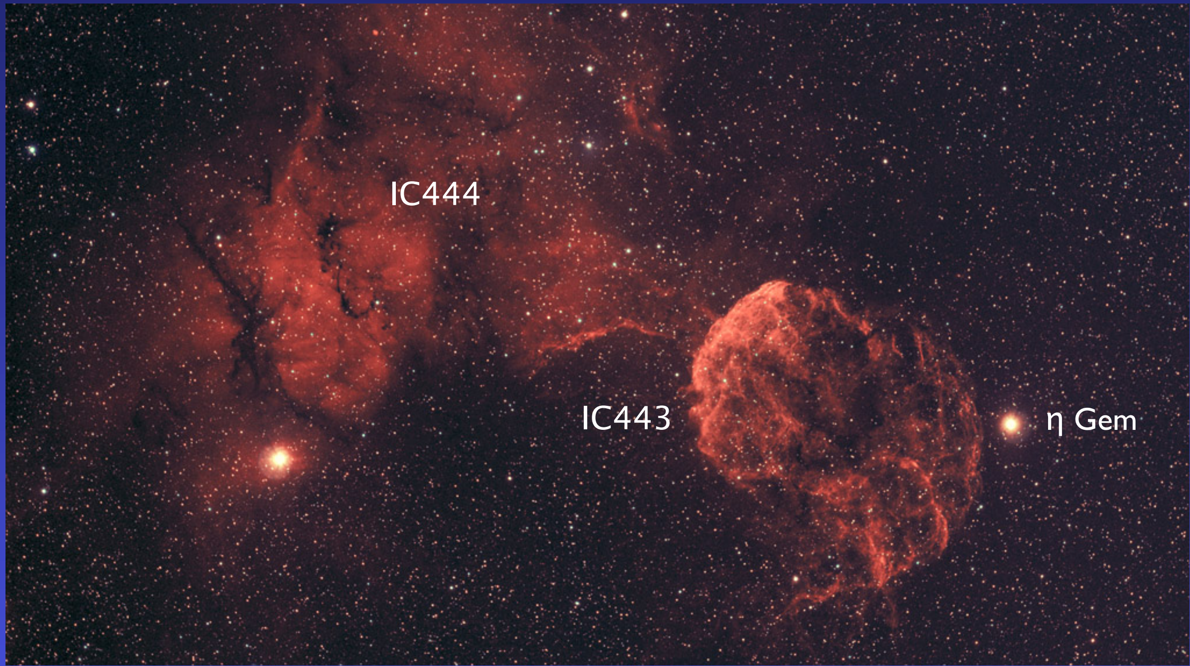
TeV

R. Wagner, in *Grenier 2008*

HESS galactic plane survey



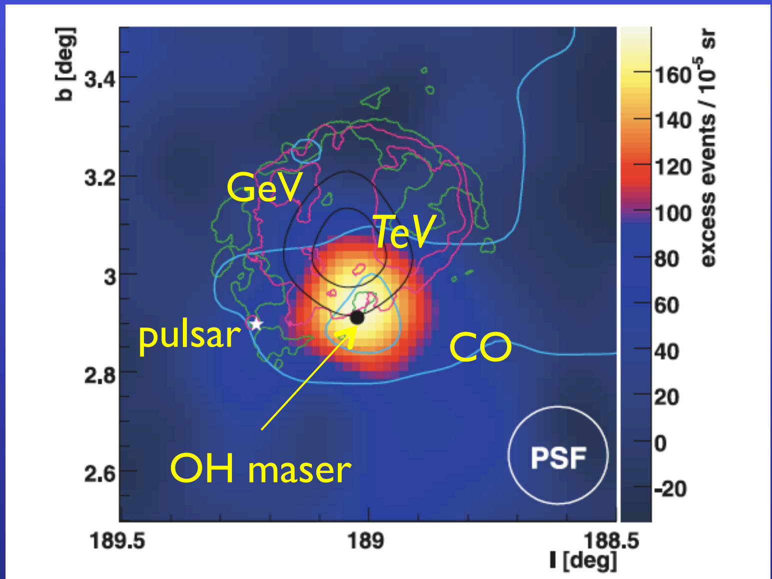
3. To be: *(a γ-ray source)*: *IC443, W28…*

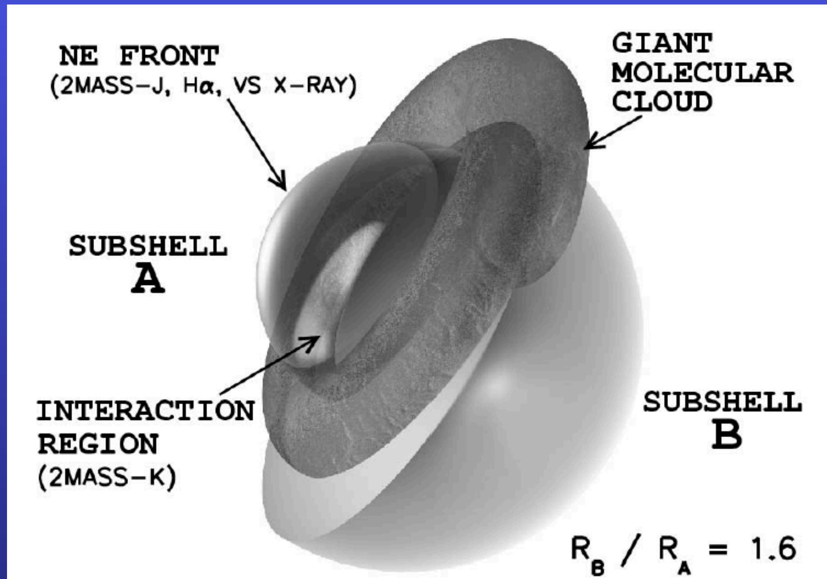


Hα

IC443 and its environment

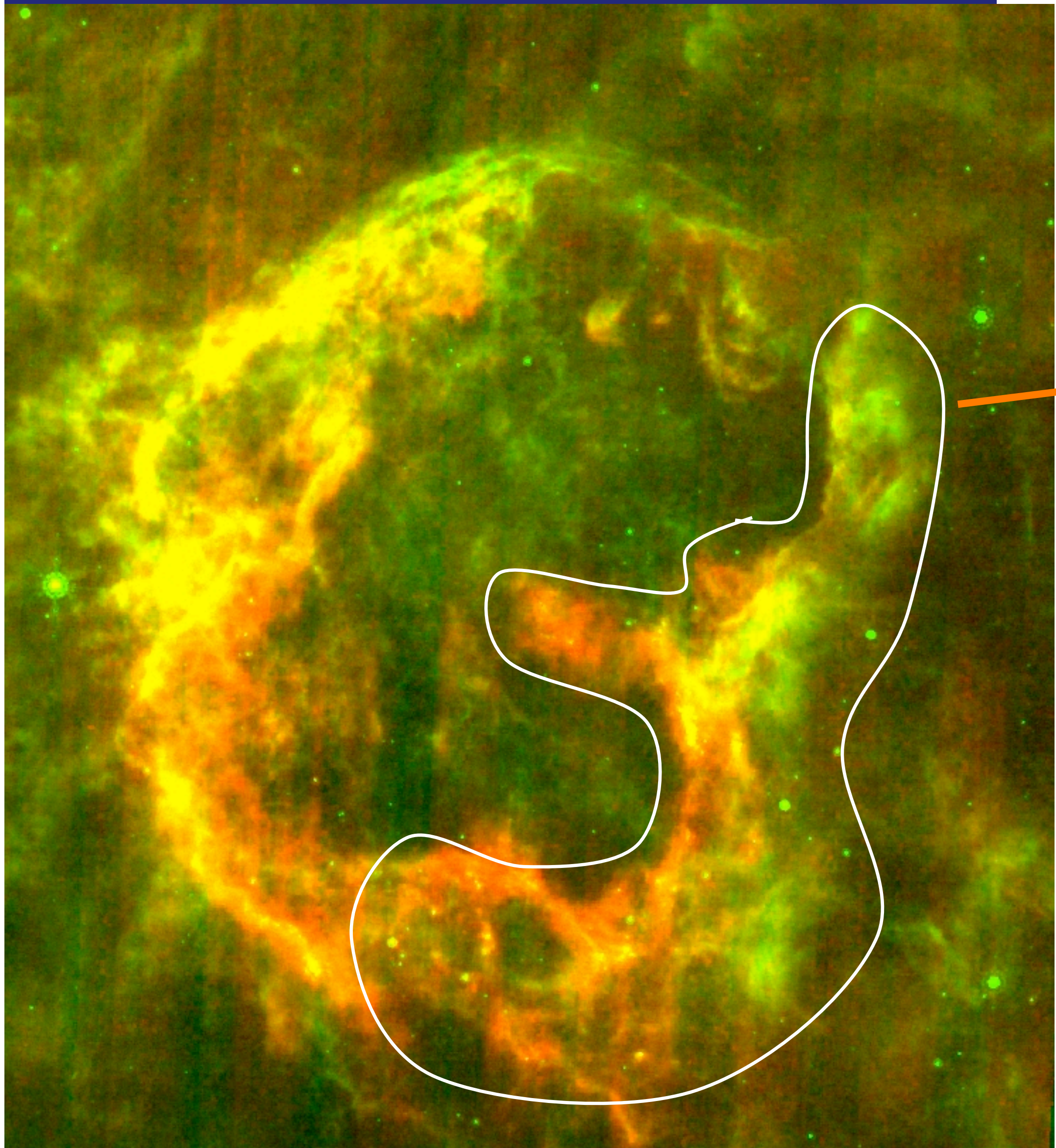
(age ~ $3x10^4$ yrs
d ~ 1.5 kpc)



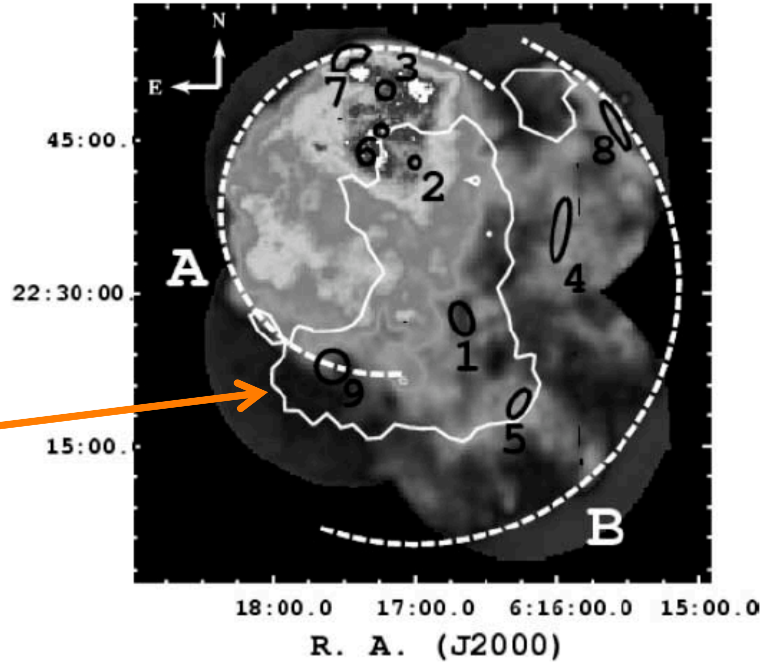


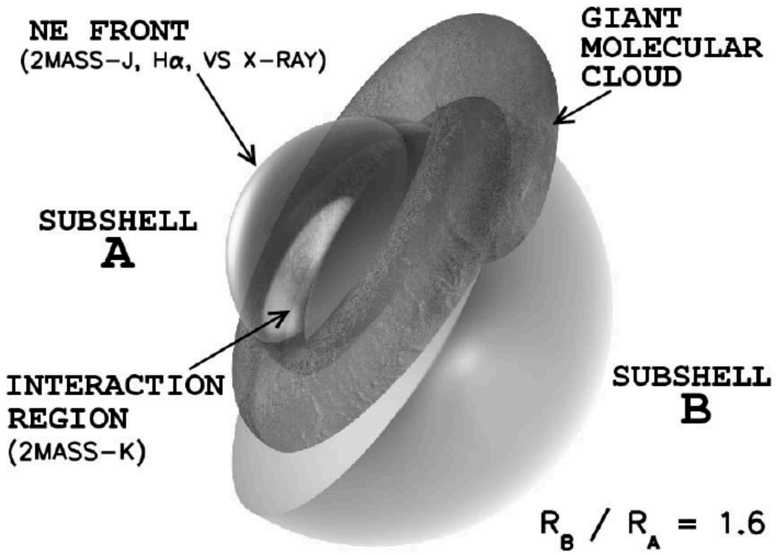
MAGIC, Canary Islands (TeV): *Albert et al. 2007*

Troja et al. 2006

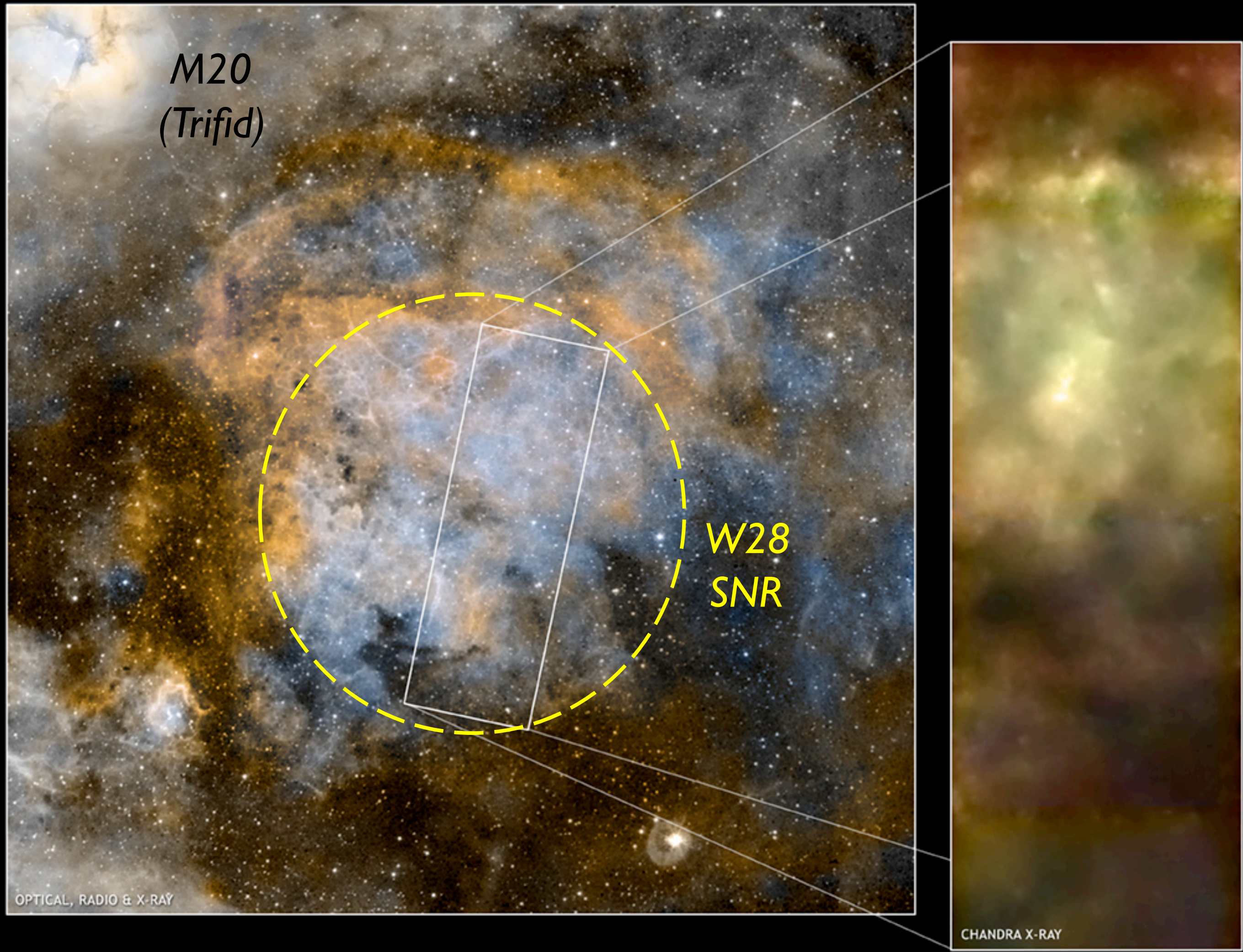


IC443: *Spitzer* (r70μm-g24μm)



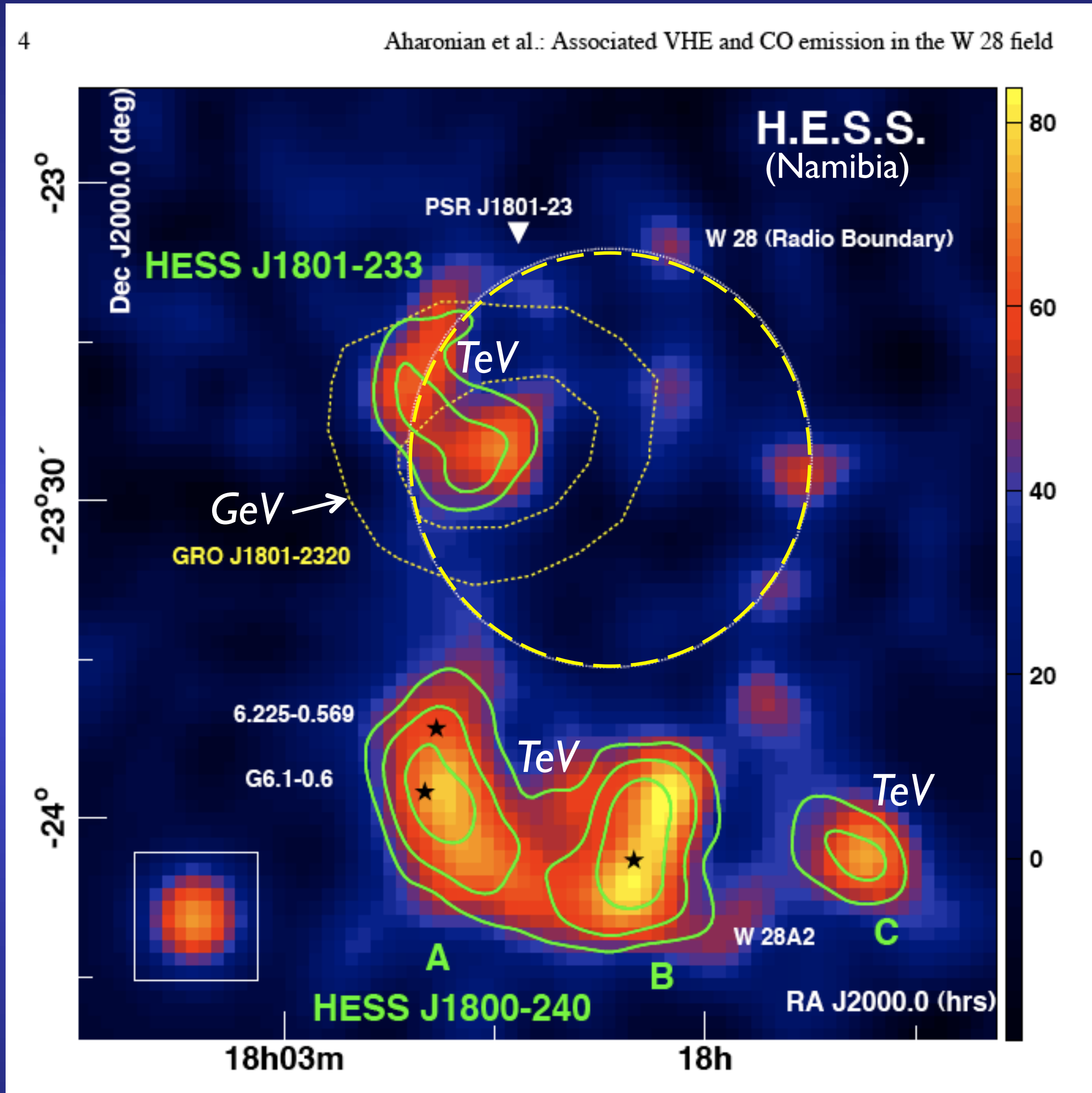


Troja et al. 2006

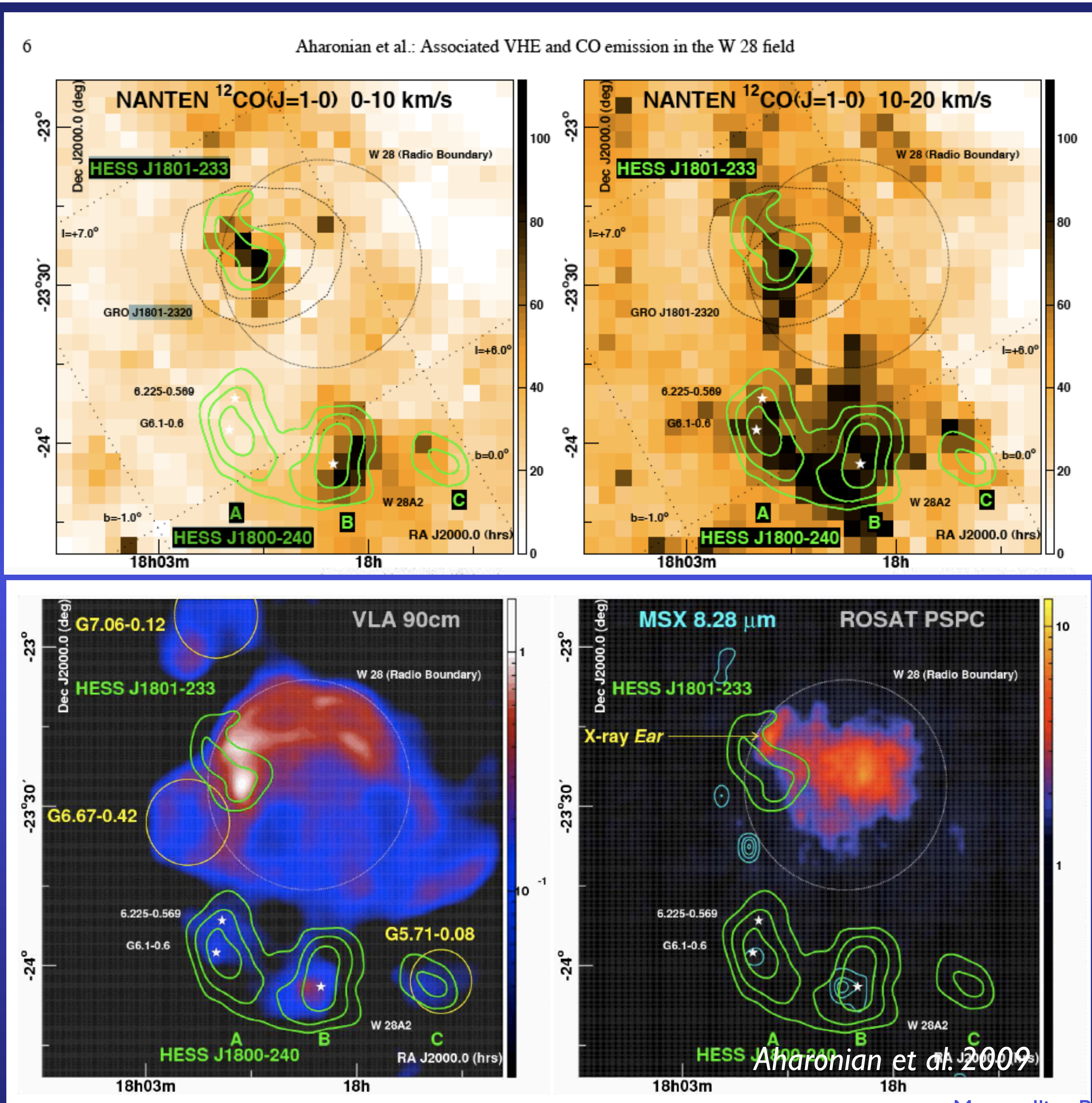


d ~ 2-3 kpc

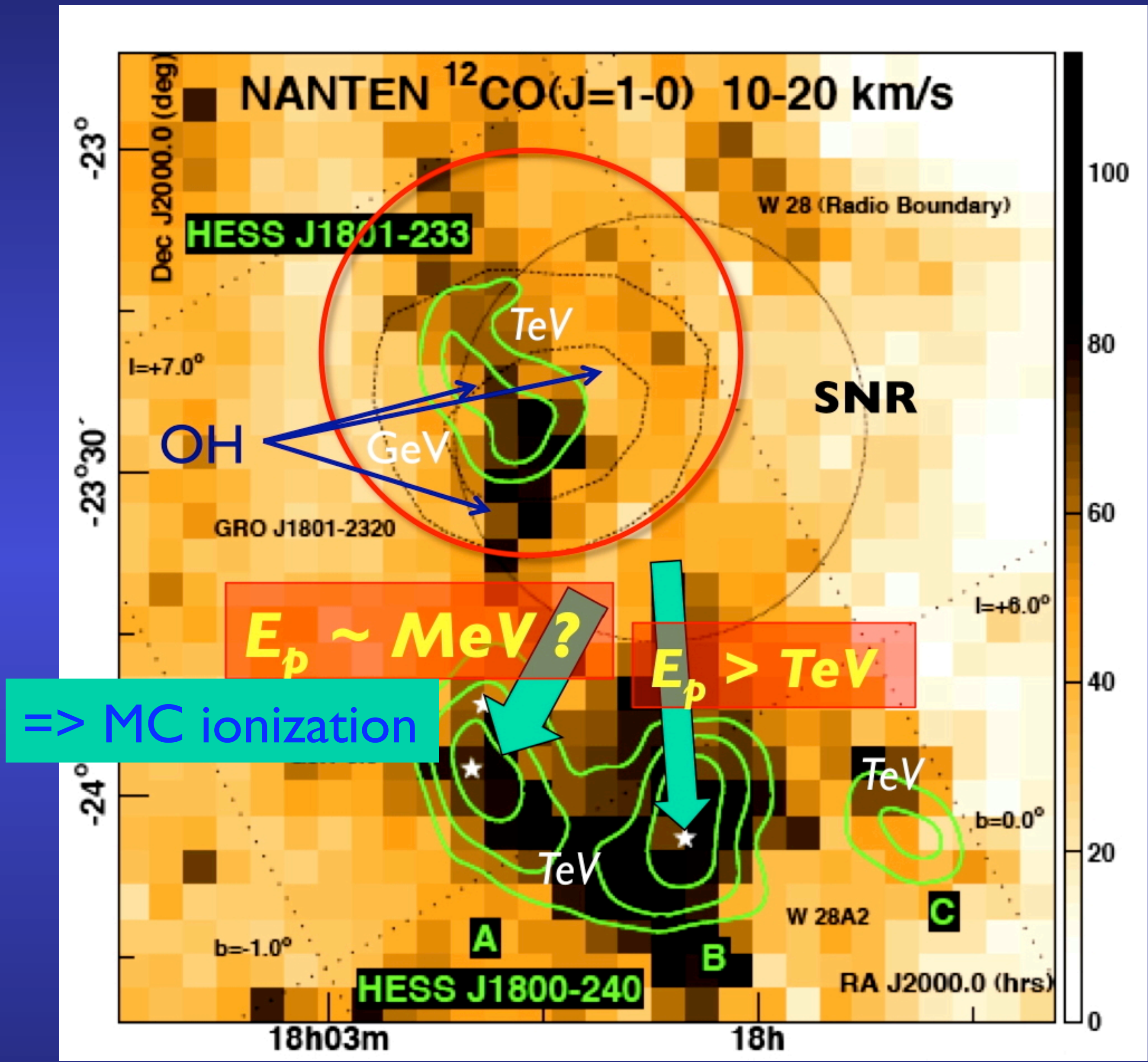
W28
SNR



Aharonian et al. 2009

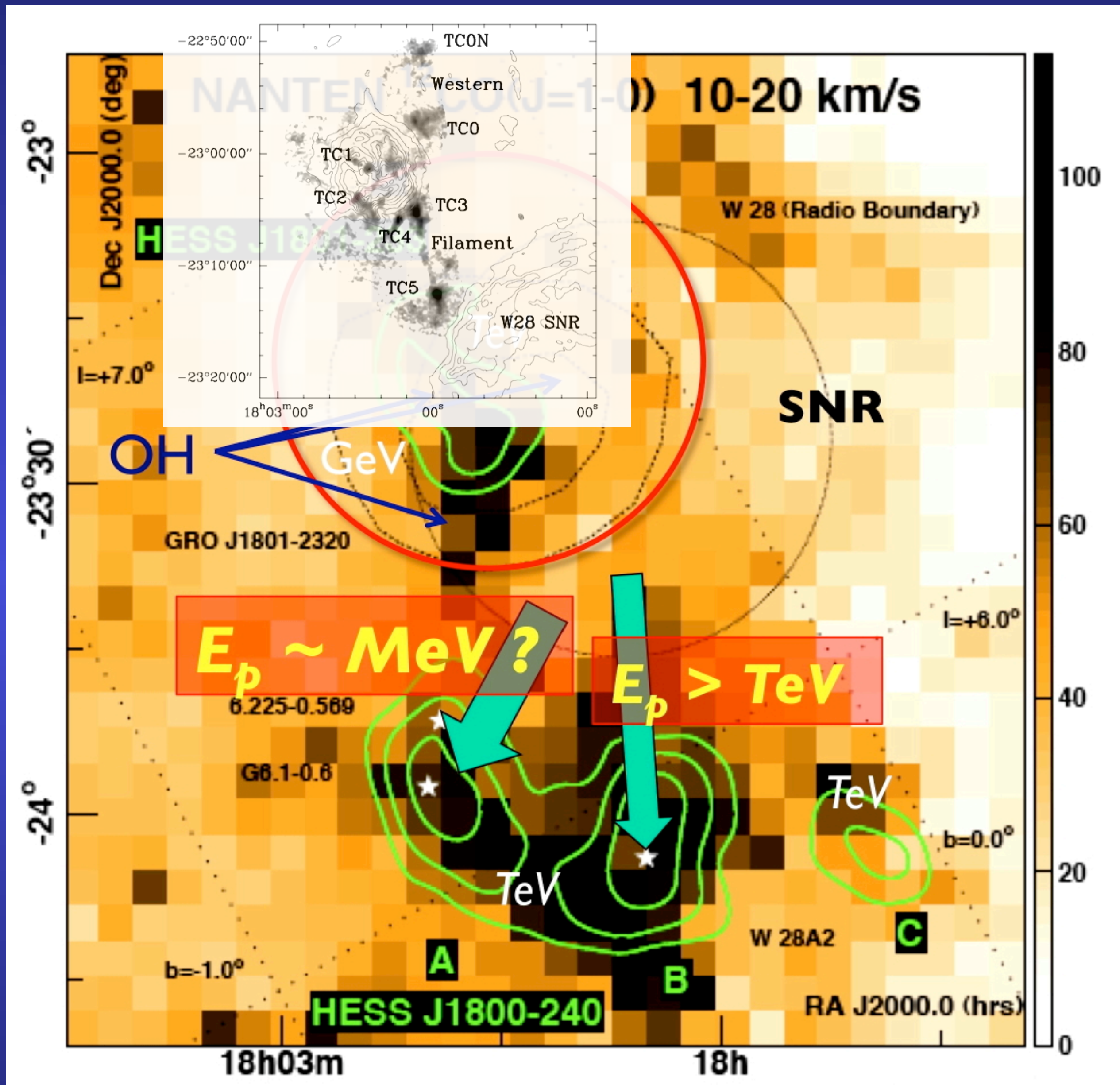


Aharonian et al. 2009

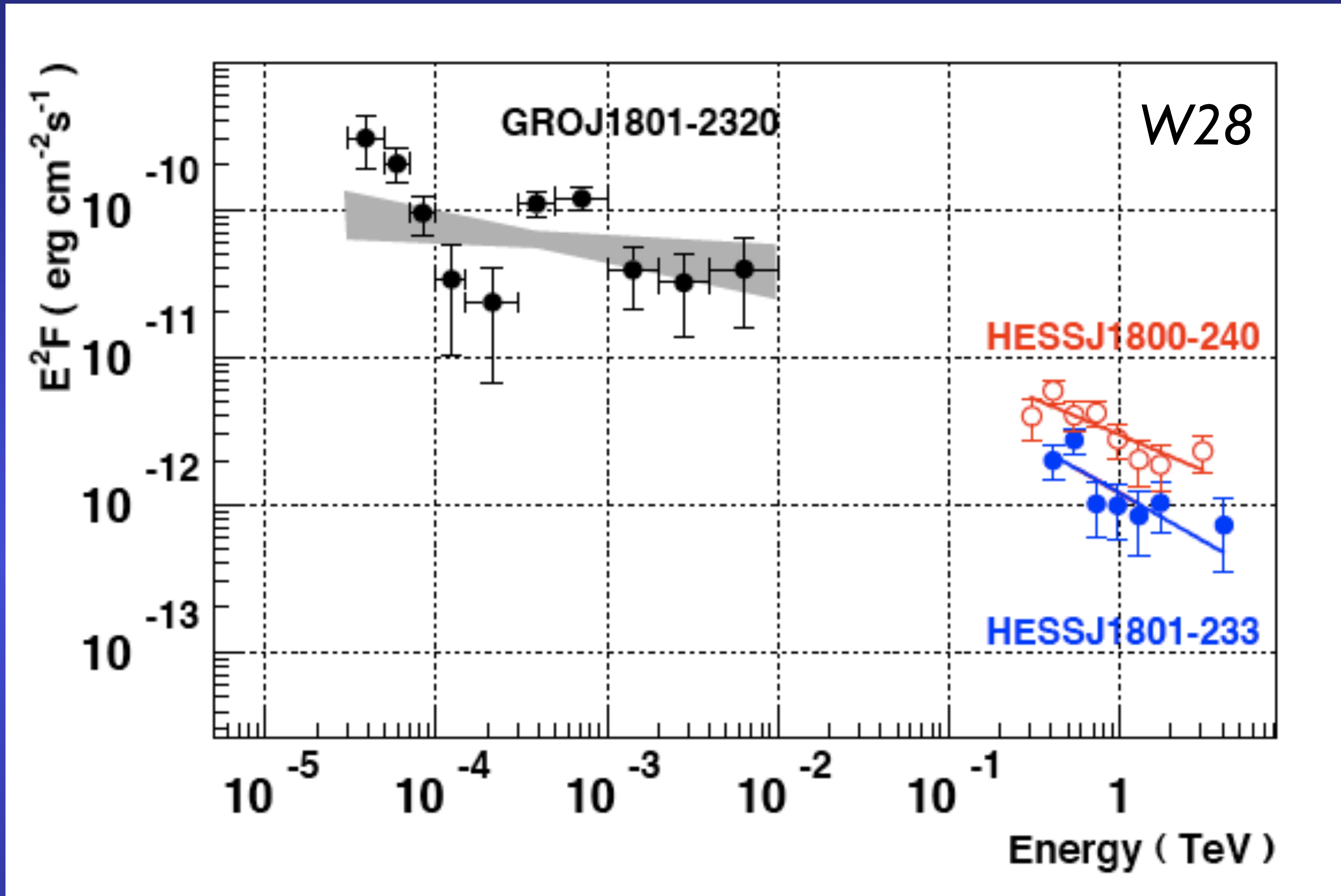


Aharonian et al. 2009

LeFloch et al. 2009



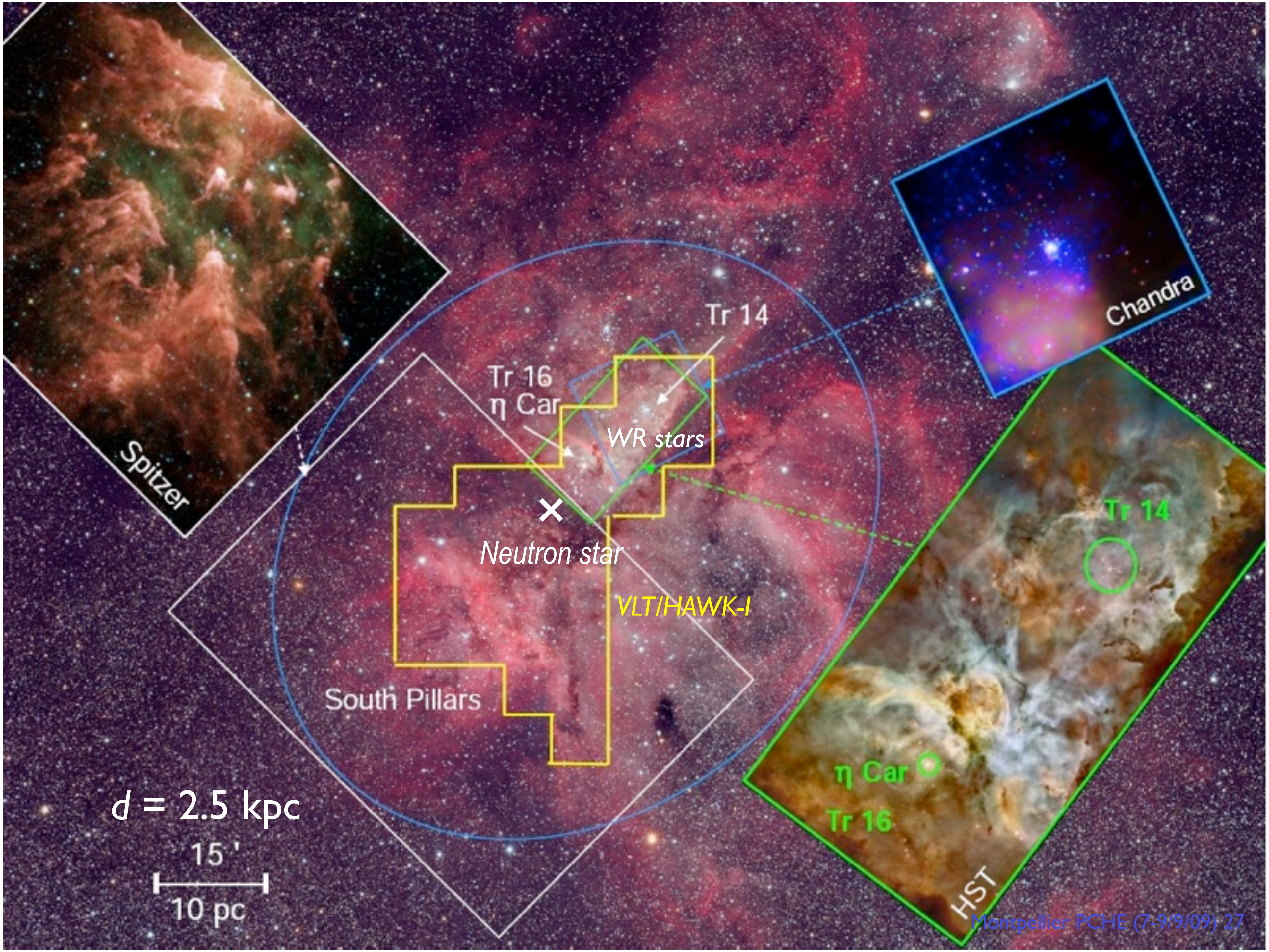
Aharonian et al. 2009

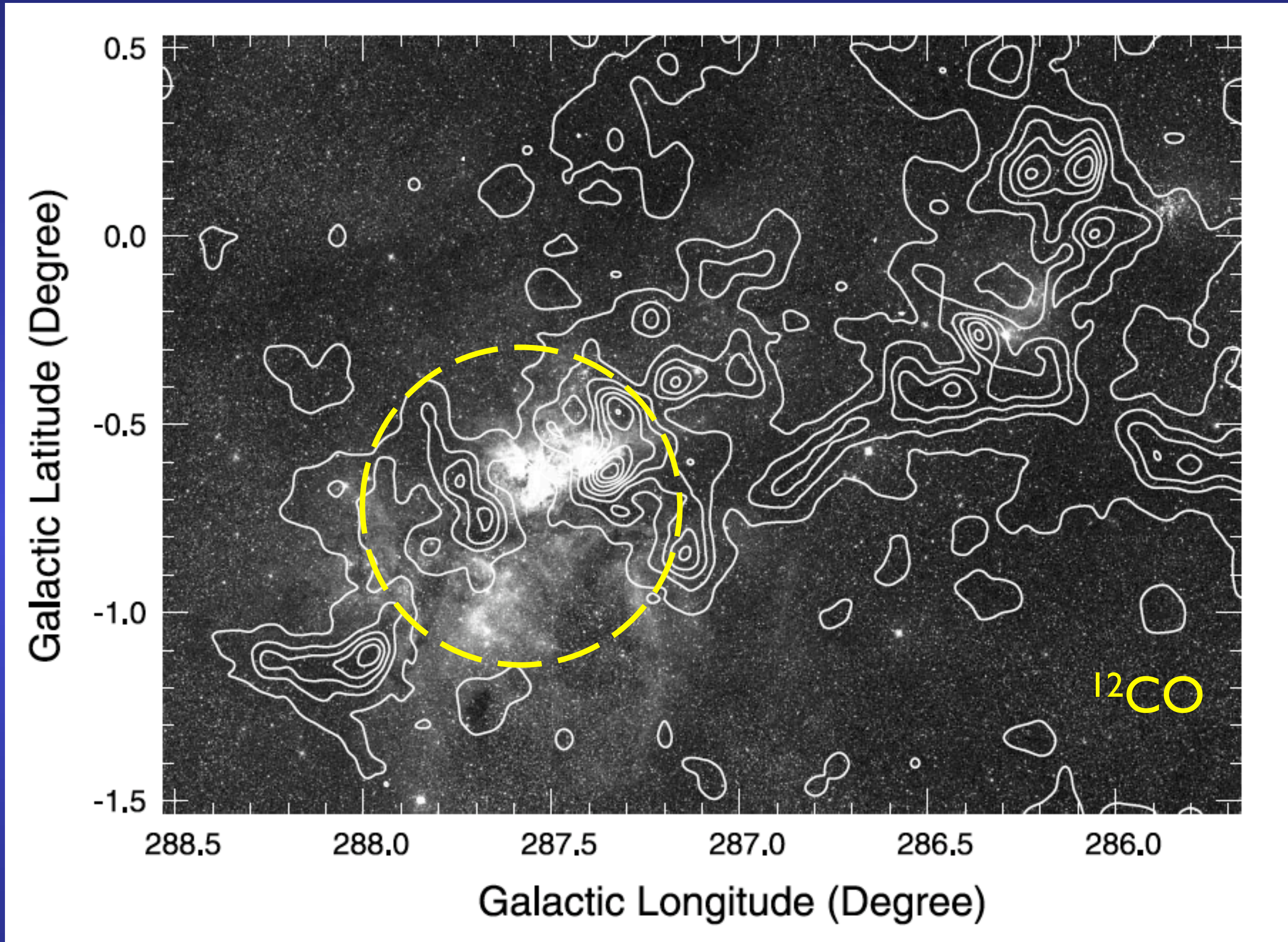


GeV-TeV spectrum compatible with π° decay; where is(are) the accelerator(s) ?

Aharonian et al. 2009

4. Not to be: *(a γ-ray source): Carina*

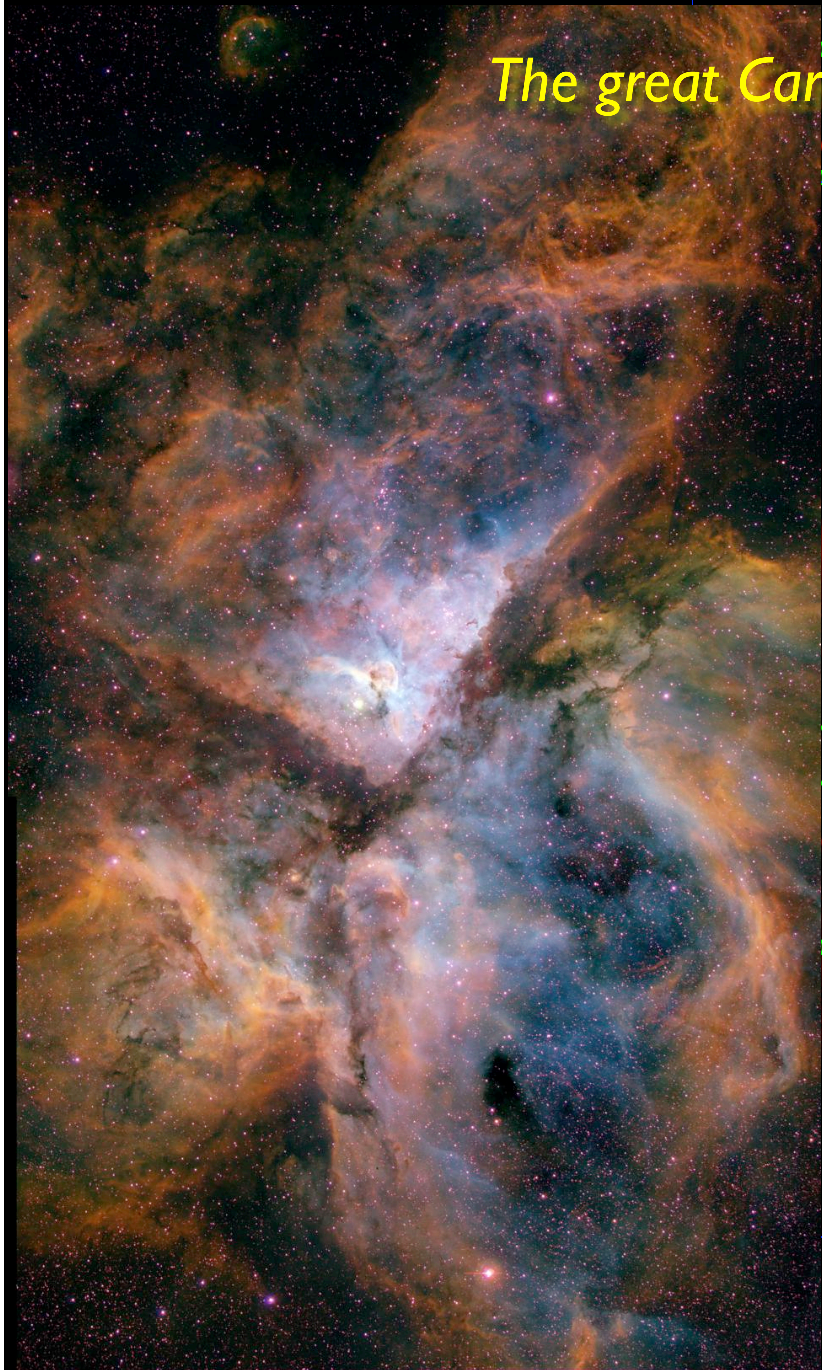

Spitzer
Chandra
Tr 14
Tr 16
η Car
WR stars
Neutron star
VLT/HAWK-I
South Pillars
HST
η Car
Tr 16
Tr 14
d = 2.5 kpc
15 '
10 pc

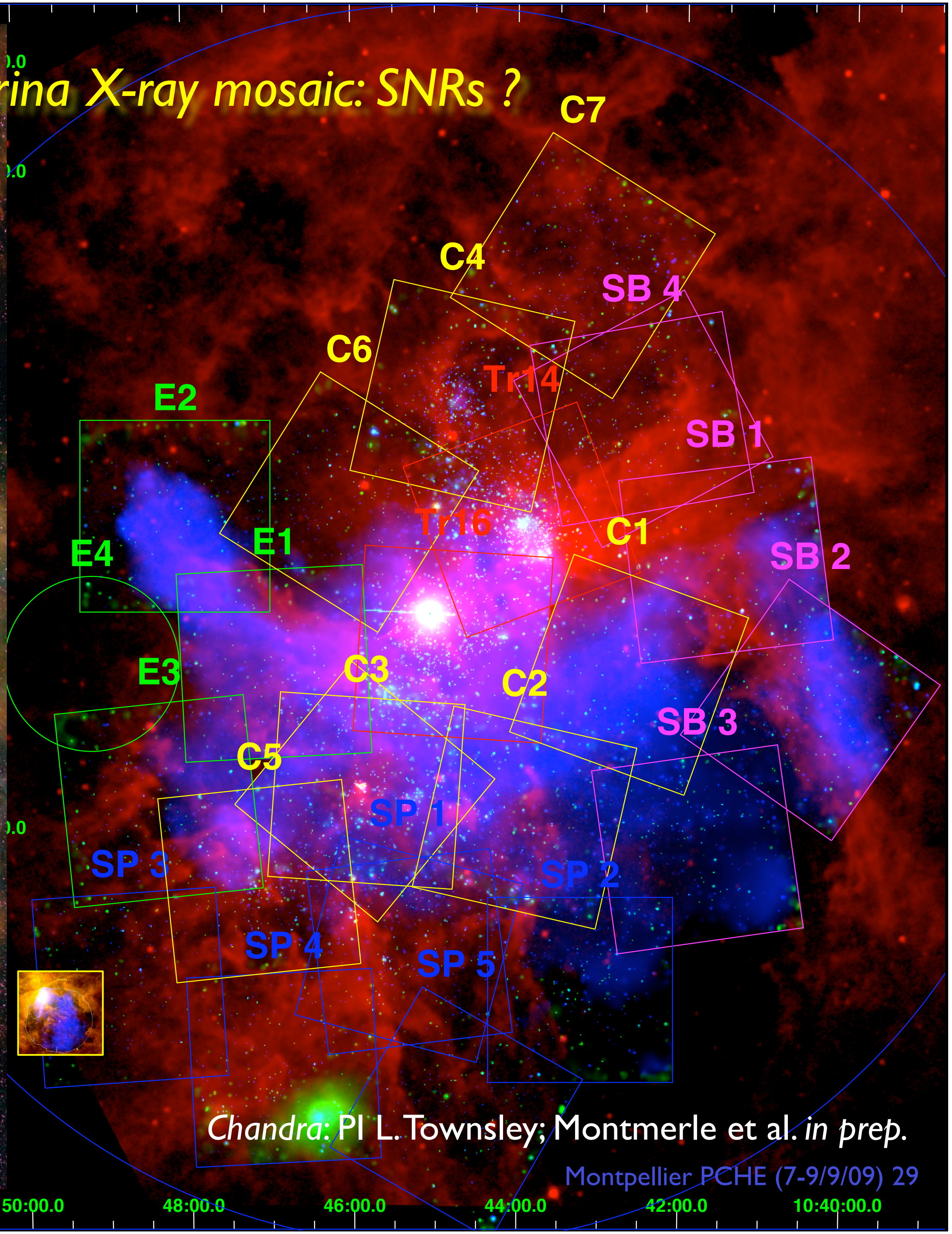


Total molecular mass ~ 3-4 x 10^5 $M_\odot$

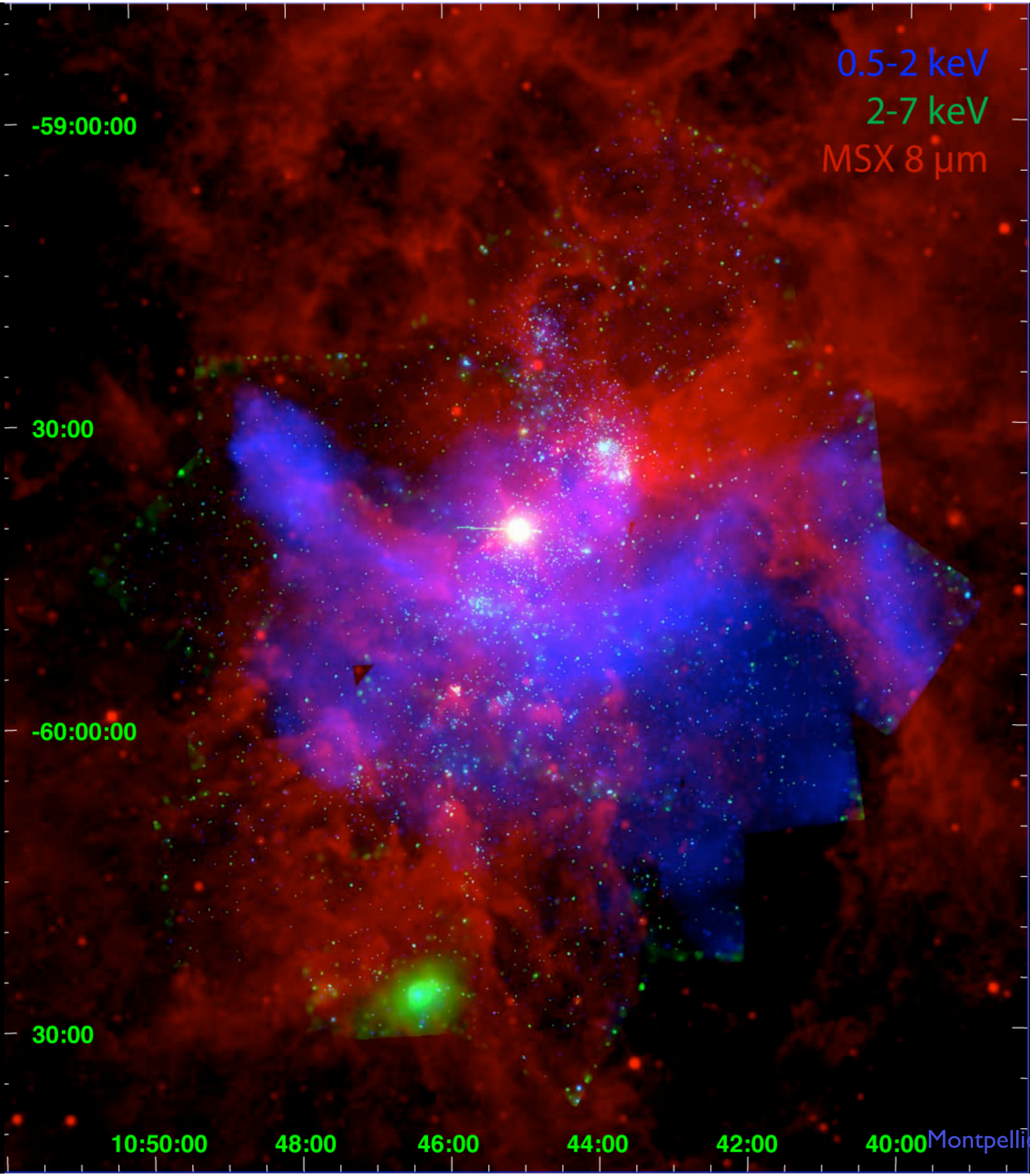
Yonekura et al. 2005

The great Carina X-ray mosaic: SNRs ?

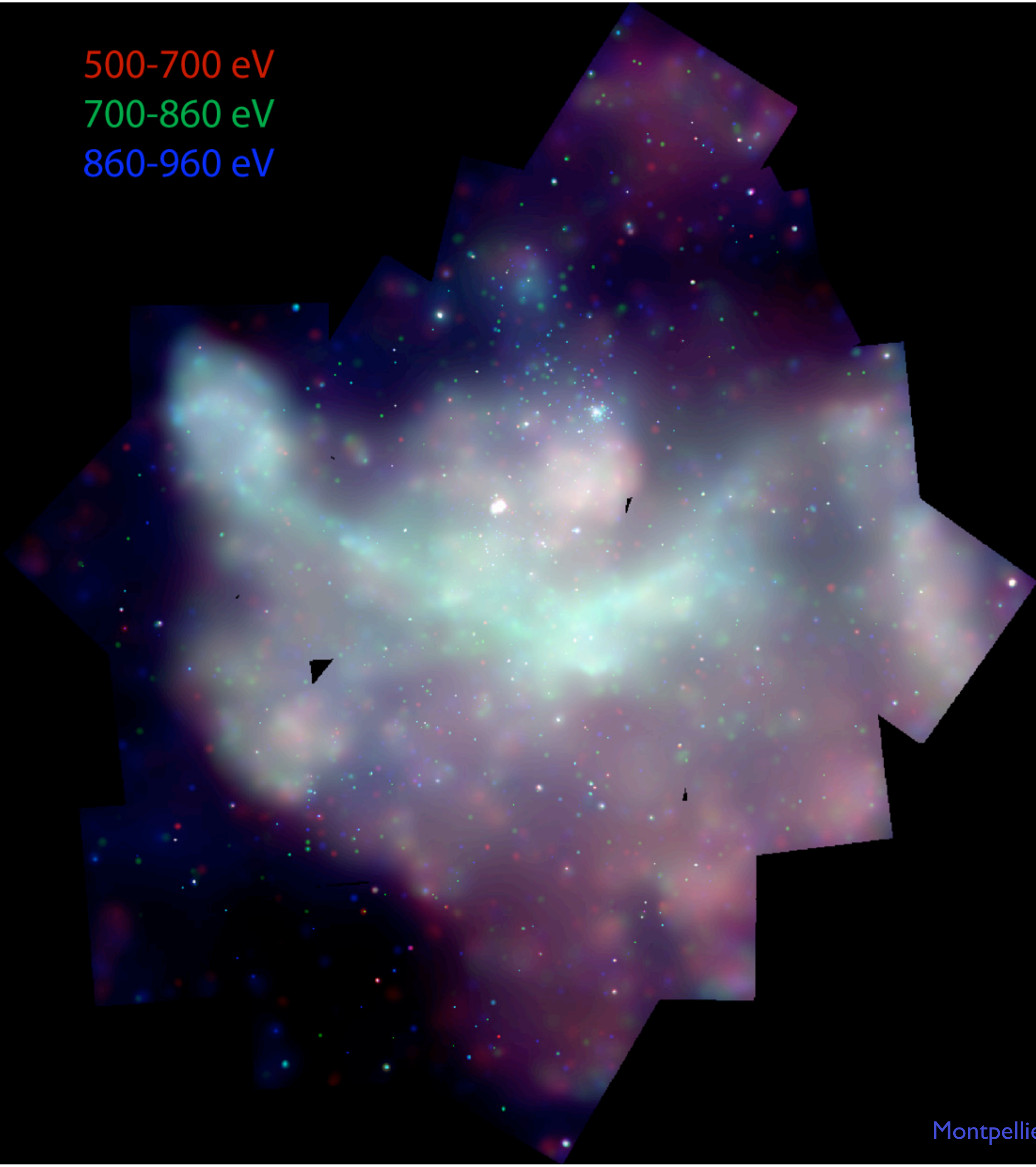




Chandra: PI L. Townsley; Montmerle et al. *in prep.*

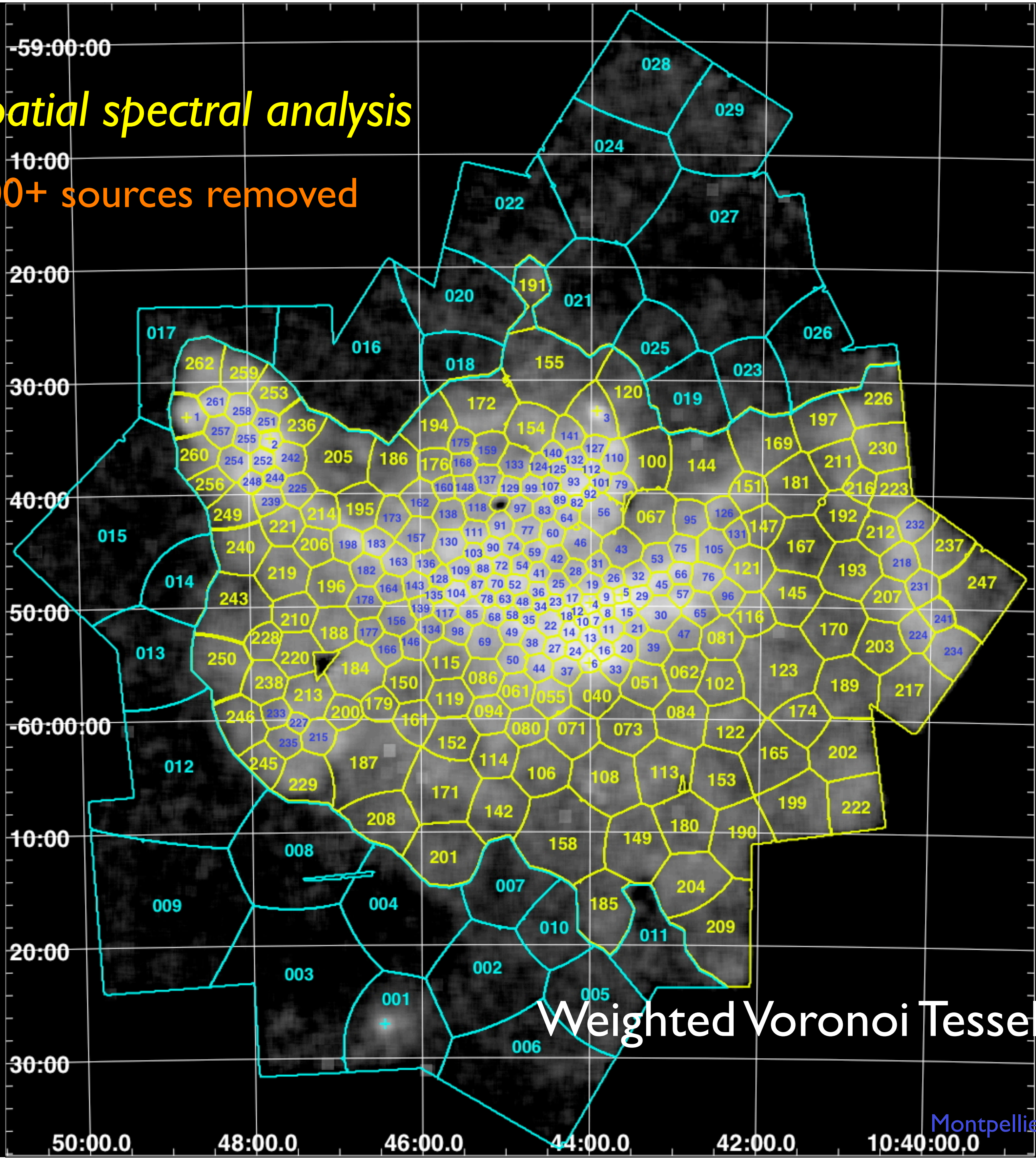

0.5-2 keV
2-7 keV
MSX 8 μm
-59:00:00
30:00
-60:00:00
30:00
10:50:00
48:00
46:00
44:00
42:00
40:00

500-700 eV
700-860 eV
860-960 eV



X-ray spatial spectral analysis

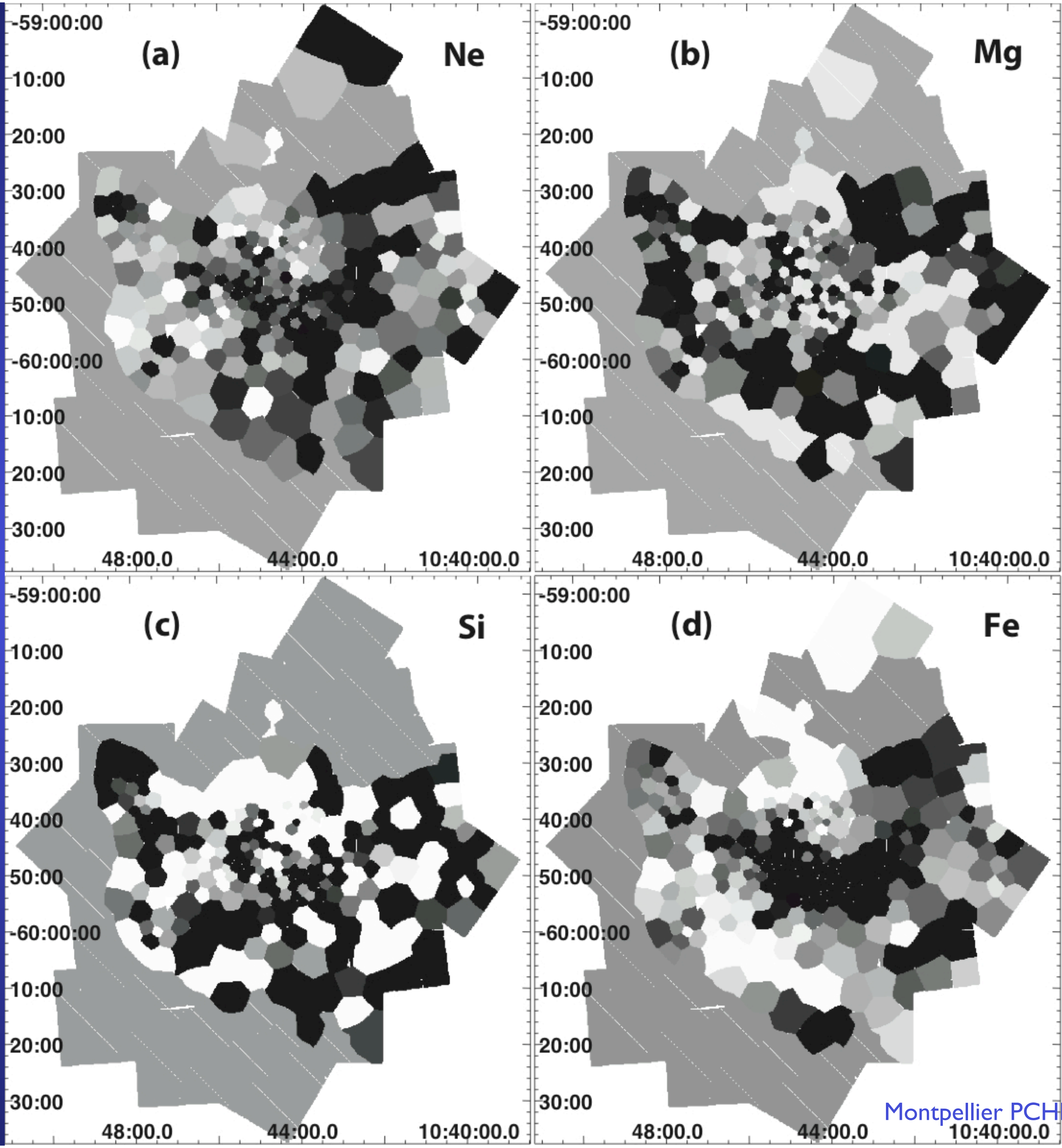
14,000+ sources removed

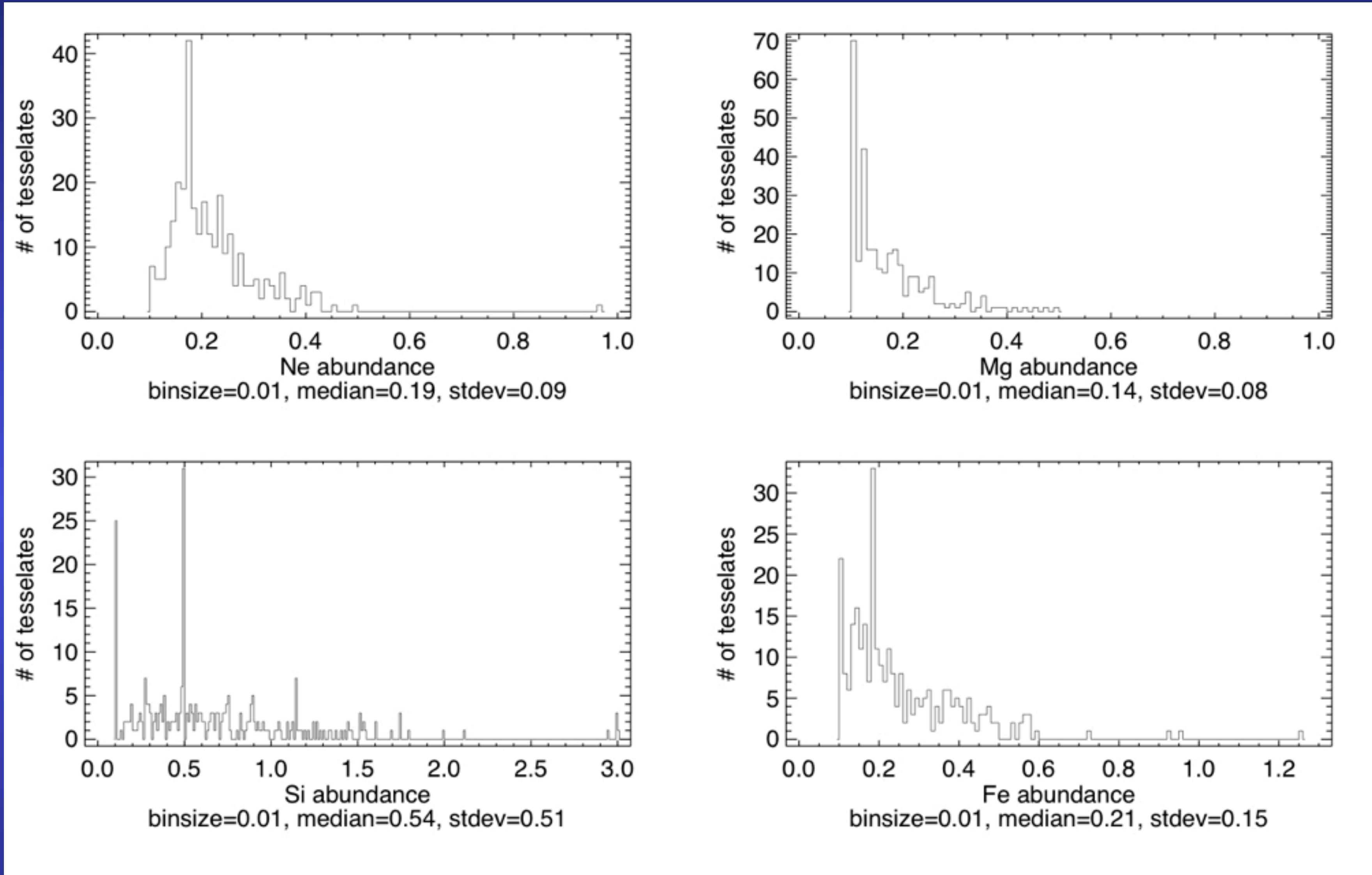


Weighted Voronoi Tesselation

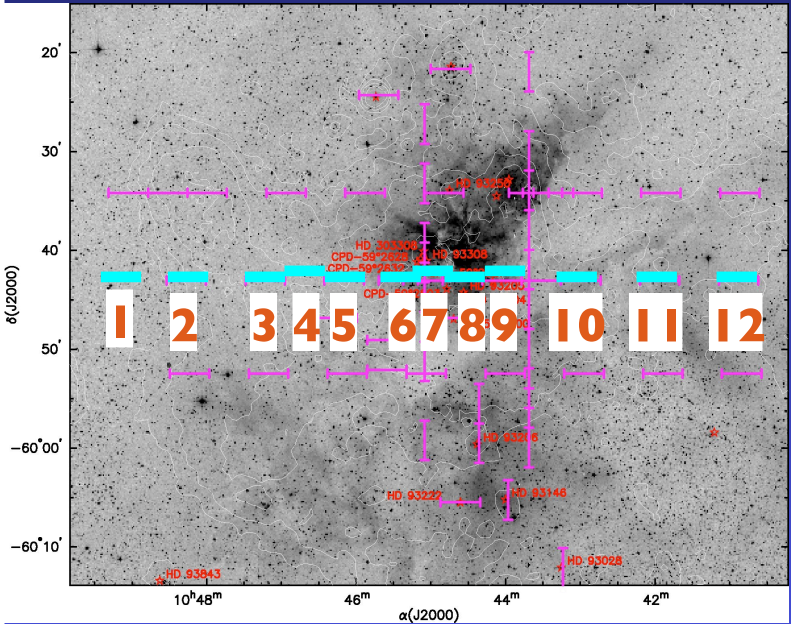
LAOG

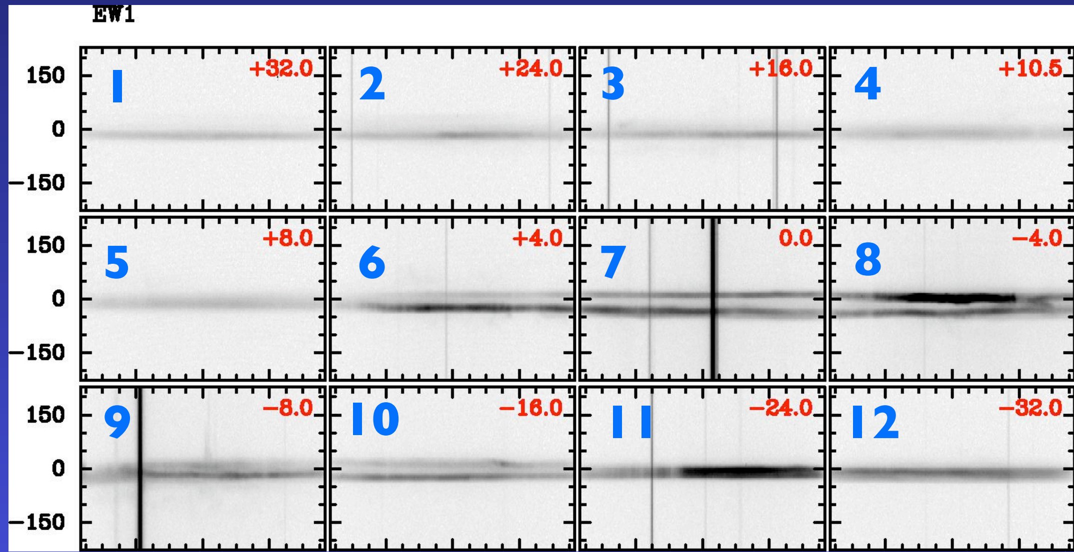
SN
ejecta ??


-59:00:00
10:00
20:00
30:00
40:00
50:00
-60:00:00
10:00
20:00
30:00
48:00.0
44:00.0
10:40:00.0
(a)
Ne
(b)
Mg
(c)
Si
(d)
Fe

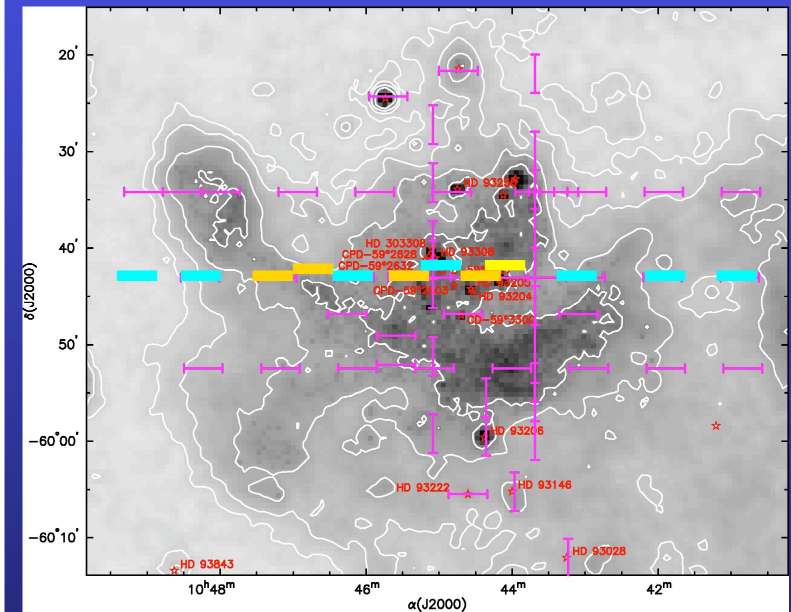


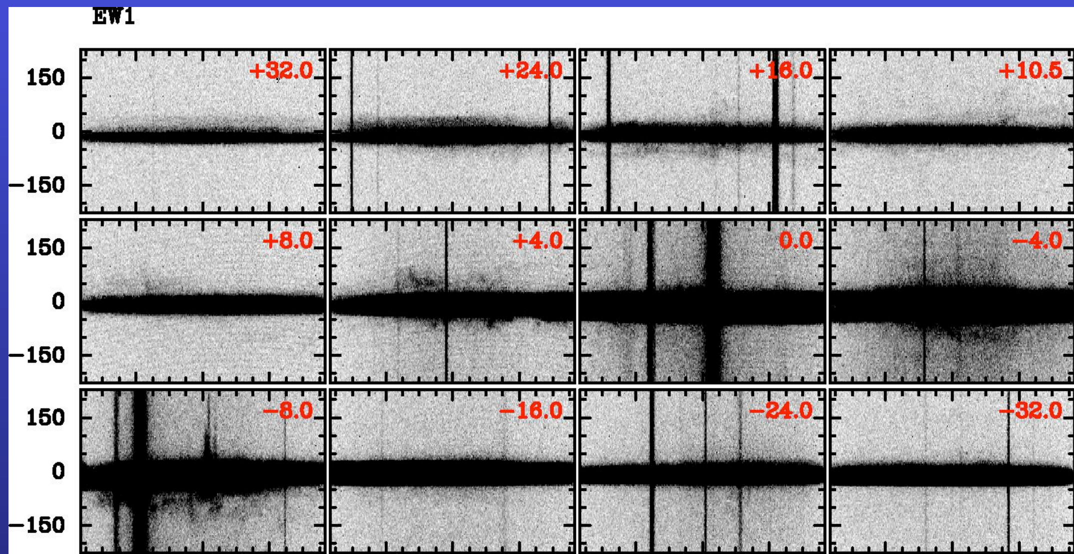
Plasma abundances (solar units): subsolar





Localized motions at ~ 50 km/s





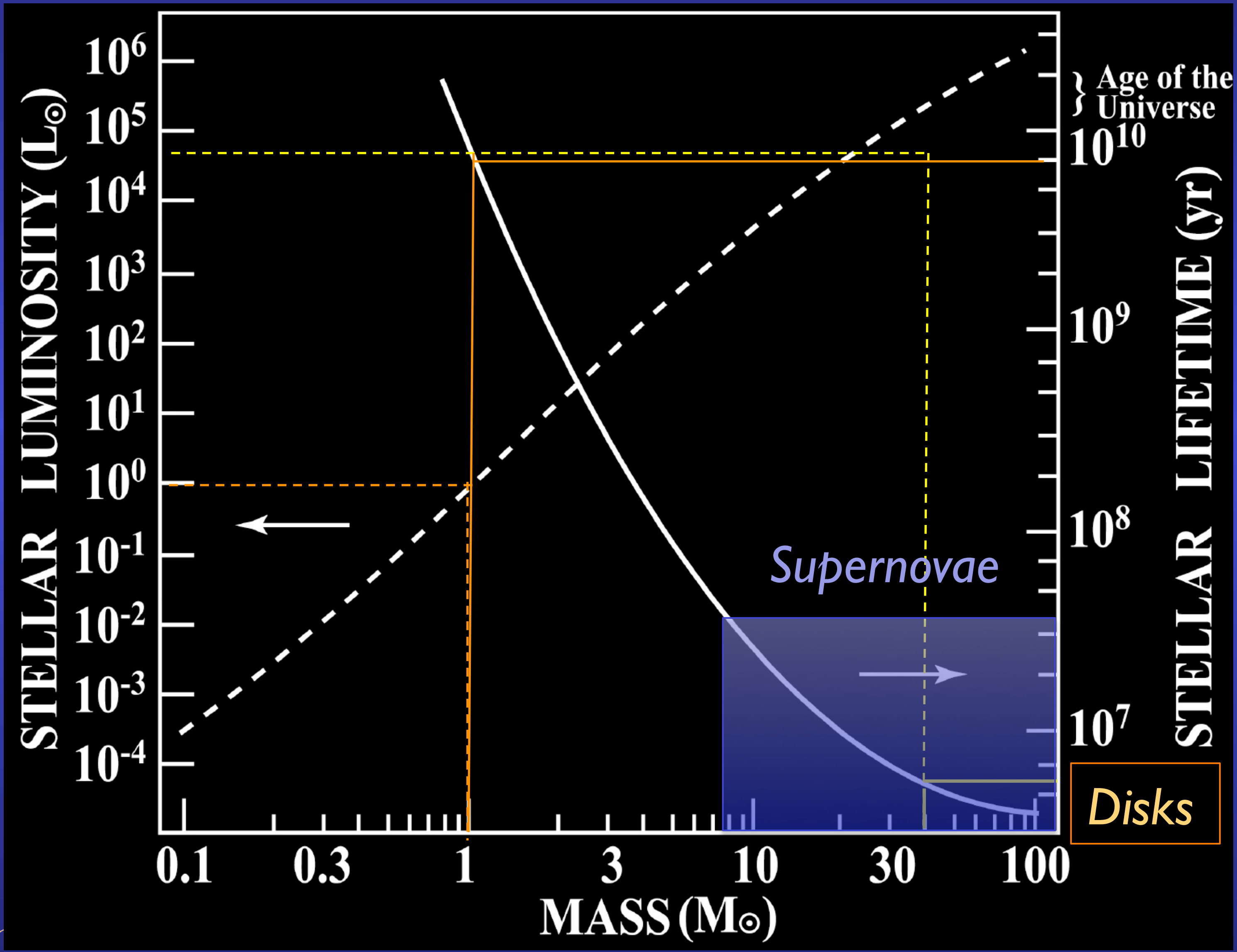
Chu et al., in prep.

- The Carina nebula is one of the most powerful SFRs in the Galaxy
  - many very massive stars: early O and WR; in dense clusters
  - indirect evidence for SN: neutron star, high-speed motions…
  - but no evidence for SN nucleosynthesis
- Otherwise seem similar to most massive SFRs, albeit more evolved (many past SN ?)
- Yet no evidence (Fermi, HESS) for excess GeV-TeV emission
- Possible reasons:
  - No SNR present
  - SNR present, but no shock
  - SNR present, shocks, but accelerated CR stay confined in hot plasma (little mass)
  - *Note*: no emission from the dense clusters
- X-ray evidence for extended hot gas (SW+SN ?): key factor ?

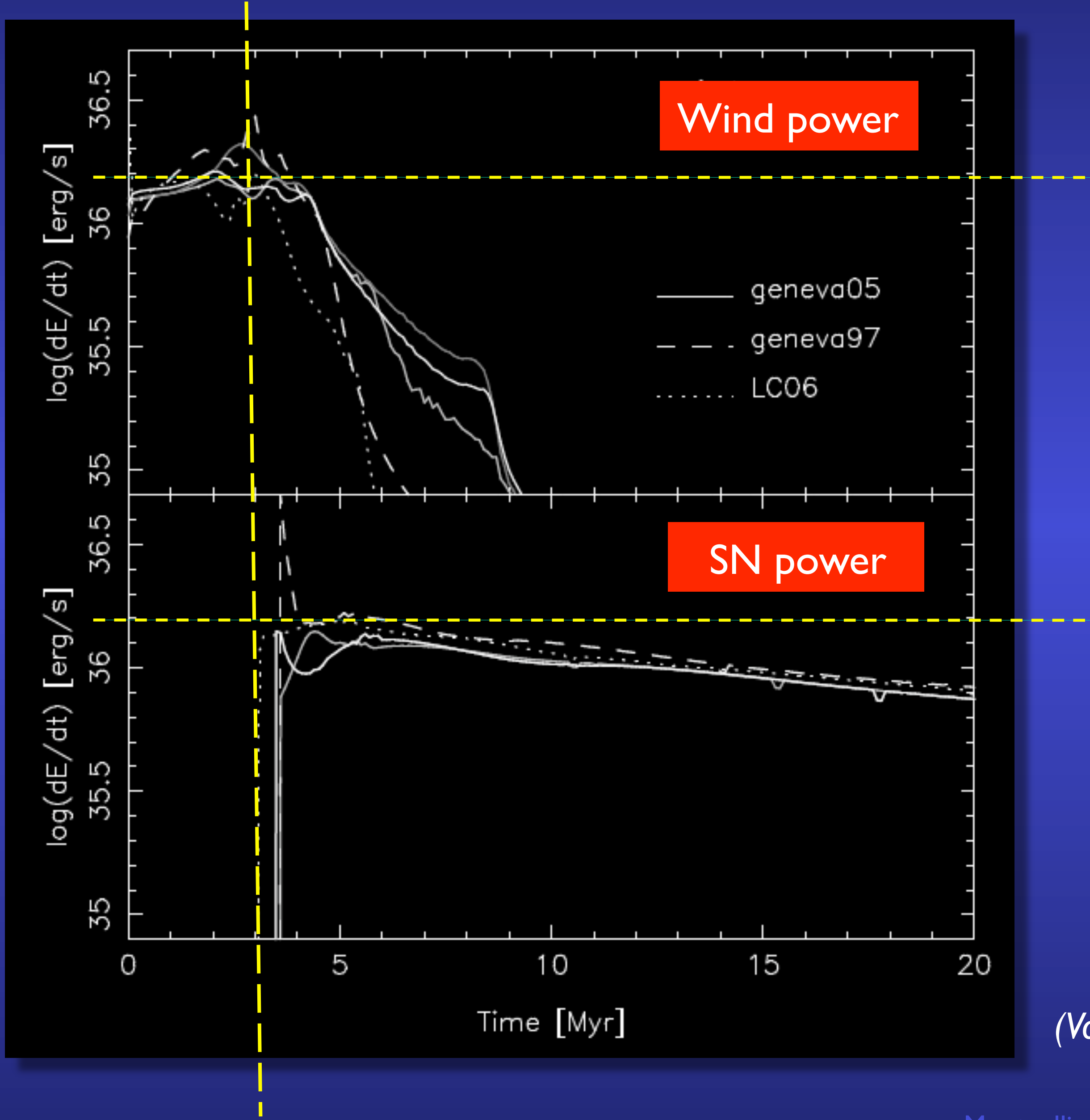
LAOG Laboratoire d'AstroPhysique de Grenoble

5. Making sense ?

Stellar and disk lifetimes vs. supernovae

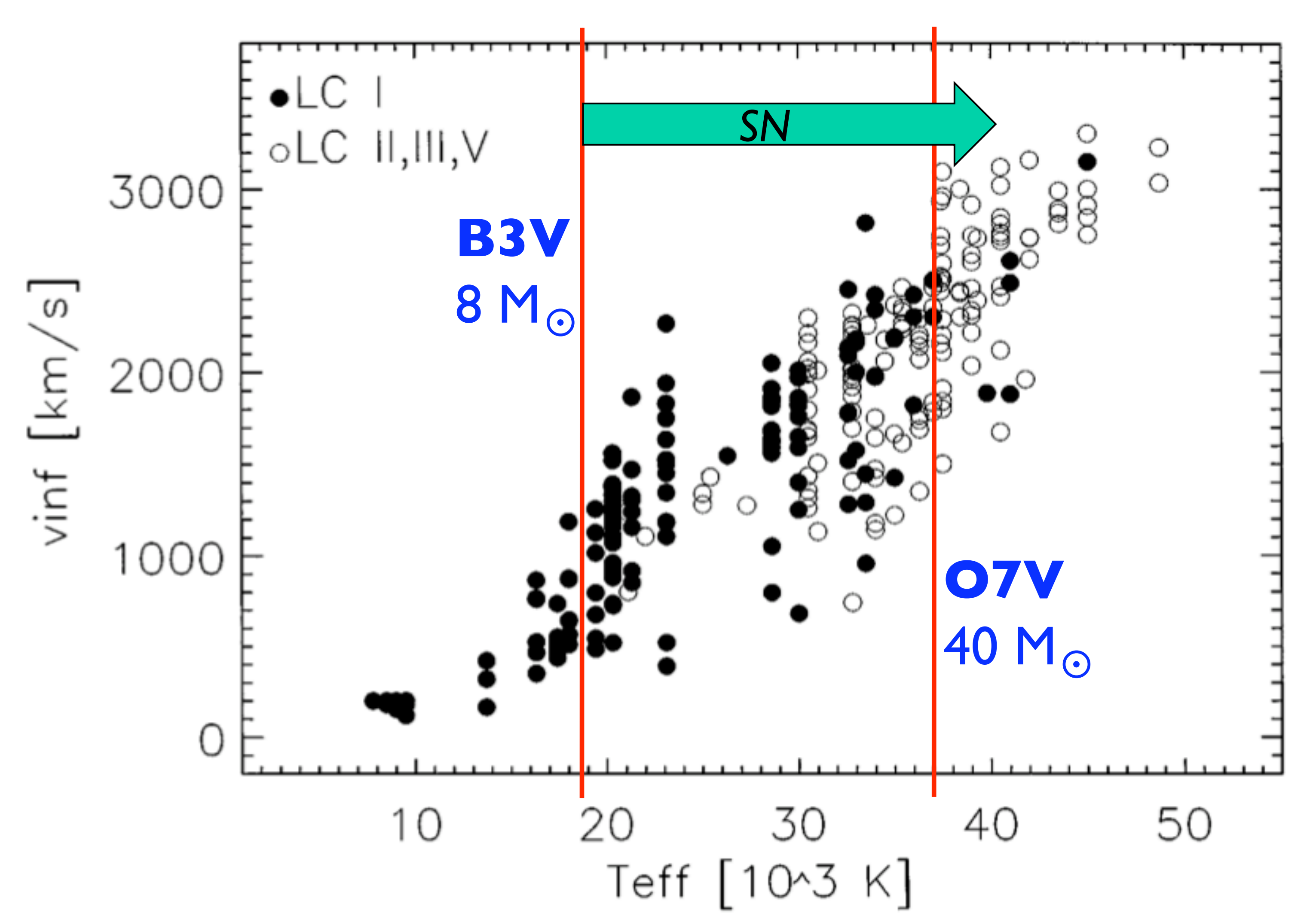


Energy output history of a (coeval) 8-120 $M_\odot$ OB association



(Voss et al. 2009)

OB stars: Wind terminal velocity

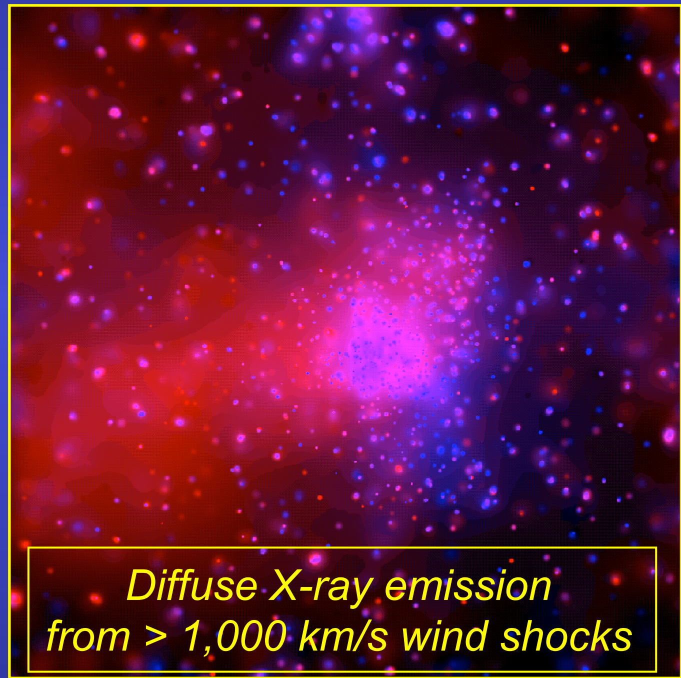


Kudritzki & Puls 2000

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

2MASS (near-IR: 2 μm)

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

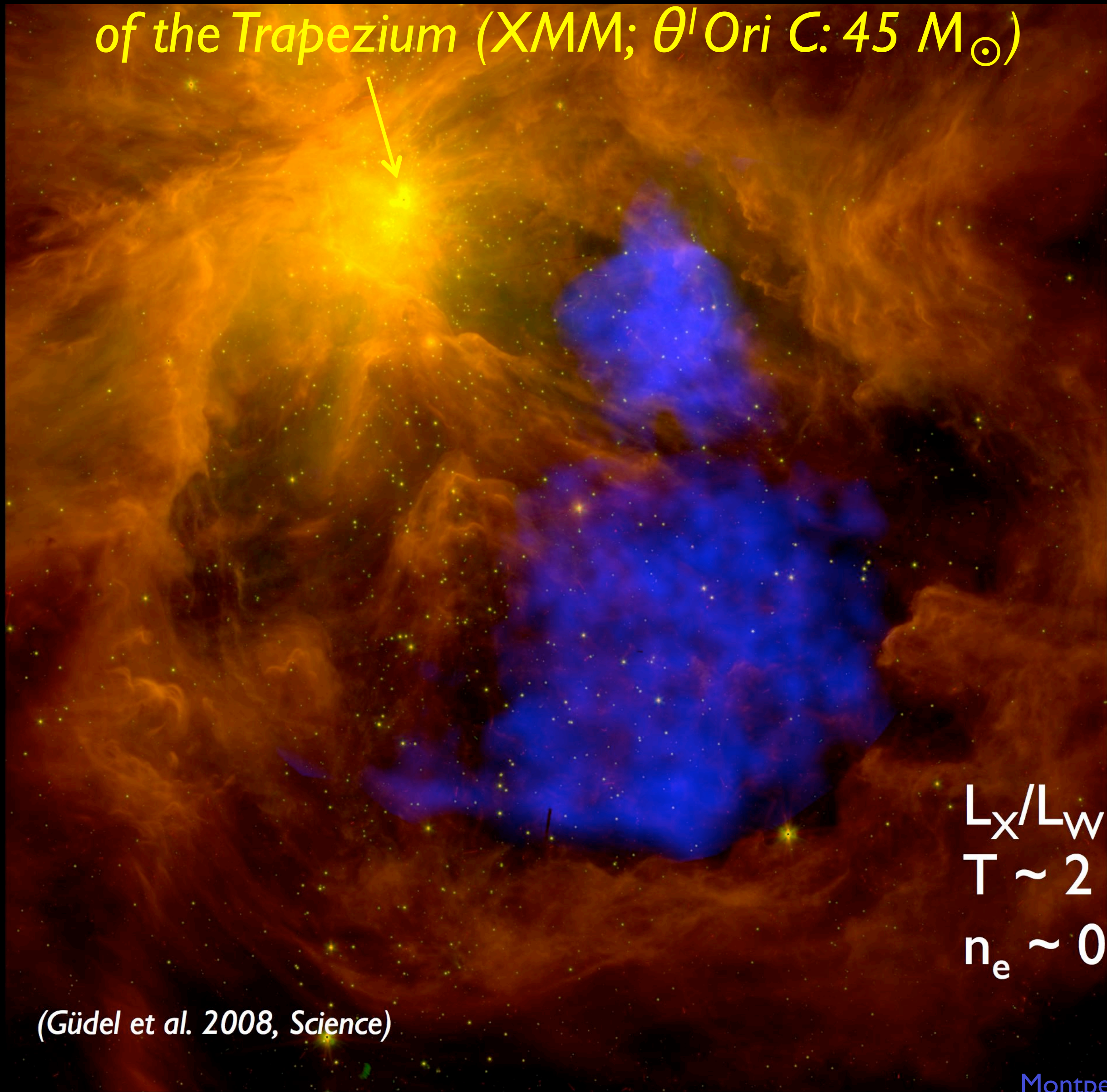


d ~ 2 kpc, ≥ 13 O (O3–>O9.5) + 34 B + x 1000 T Tauri stars

No WR star *(Townsley, Montmerle, et al. 2003, ApJ)*

LAOG

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



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

$T \sim 2$ MK

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

(Güdel et al. 2008, Science)

6. Concluding remarks

- Massive star-forming regions containing SNRs (from SNII explosions) are now a well-established class of γ-ray sources (GeV and/or TeV)
- In situ cosmic-ray acceleration is expected to be directly observable via MeV interactions with neighbouring molecular clouds: *enhanced ionization (talk by PHB)*
- γ-rays => observational census of SNRs in OB associations: *link of SNOBs with the "cradle of the Sun" debate* ("extinct radioactivities" in meteorites) *(talk by MG)*
- But maximum-mass- and time-dependent evolution !
  - *Working hypothesis:* probably requires not-too-massive SFR for SN shocks to exist (no pre-explosion very hot plasma from very fast winds)
  - Since CR (low-energy) irradiate/ionize molecular clouds, may mean *episodes* of enhanced (or suppressed ?) star formation !
  - Duration of enhanced γ-ray emission: a few 10^5 yrs at most (= SNR lifetime in dense environment)

LAOG

Laboratoire d'AstrOphysique de Grenoble