Dynamical Effects of Stars: Gas Shells of Different Sizes

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Shock-Production of Hot Plasma

Adiabatic shocks, post-shock temperature

$$kT = \frac{3}{16}\mu u_1^2$$

300 km/s → 10^6 K

3000 km/s → 10^8 K

Supernova remnant shocks: $10^2 - 10^4$ km/s

Fast stellar winds: 1000 – 3000 km/s

Shocked Stellar Winds in PNe, Bubbles, Superbubbles

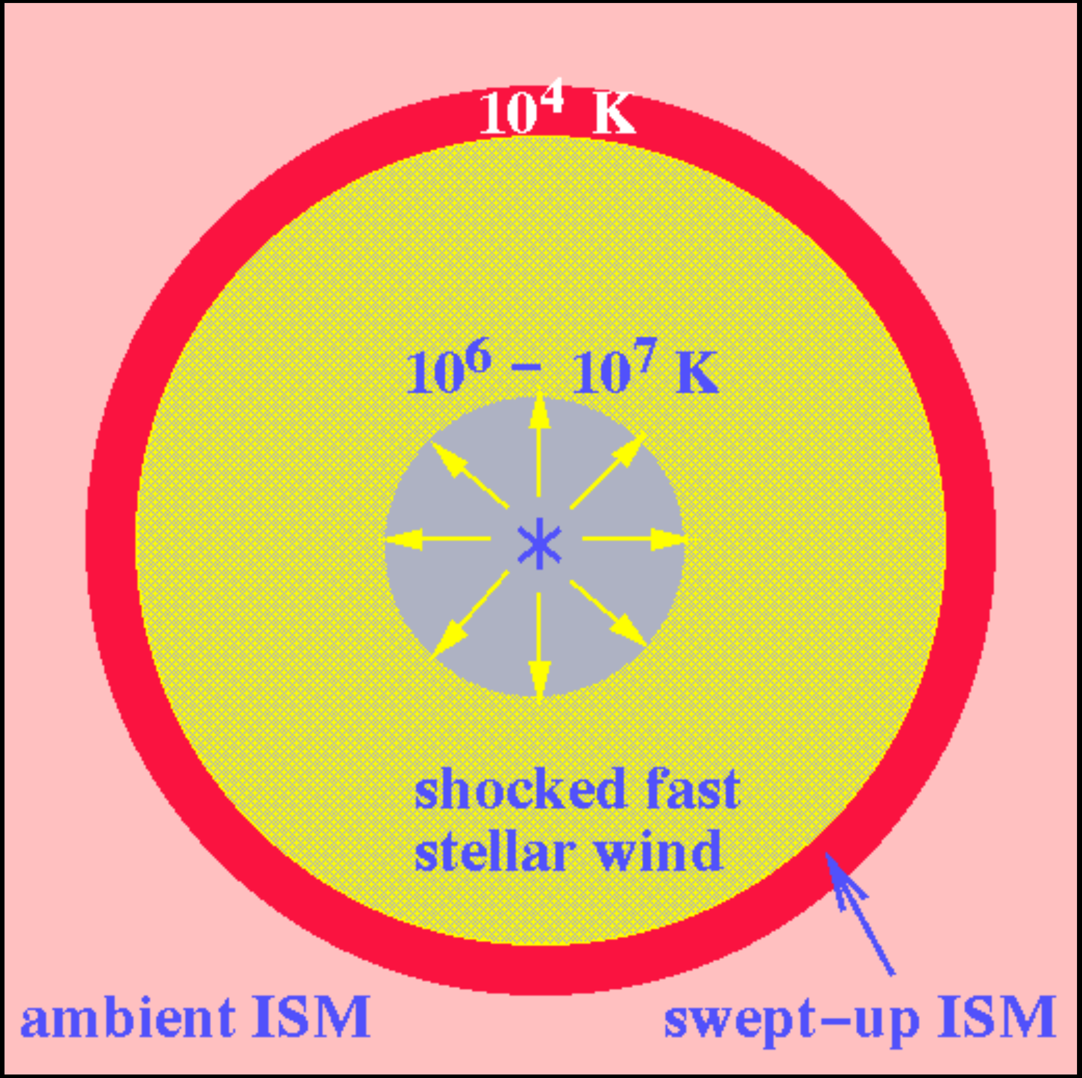
(Milky Way Objects)

Interstellar & Circumstellar Bubbles

O star →	LBV →	WR	($60\ M_\odot$)
O star →	RSG →	WR	($35\ M_\odot$)
fast wind	slow wind	fast wind	
1000 - 2000 km/s	10 - 50 km/s	2000 - 3000 km/s	
$10^{-7}\ M_\odot$/yr	$10^{-4}\ M_\odot$/yr	$10^{-5}\ M_\odot$/yr	
↓	↓	↓	
interstellar bubble	circumstellar nebula	circumstellar bubble	

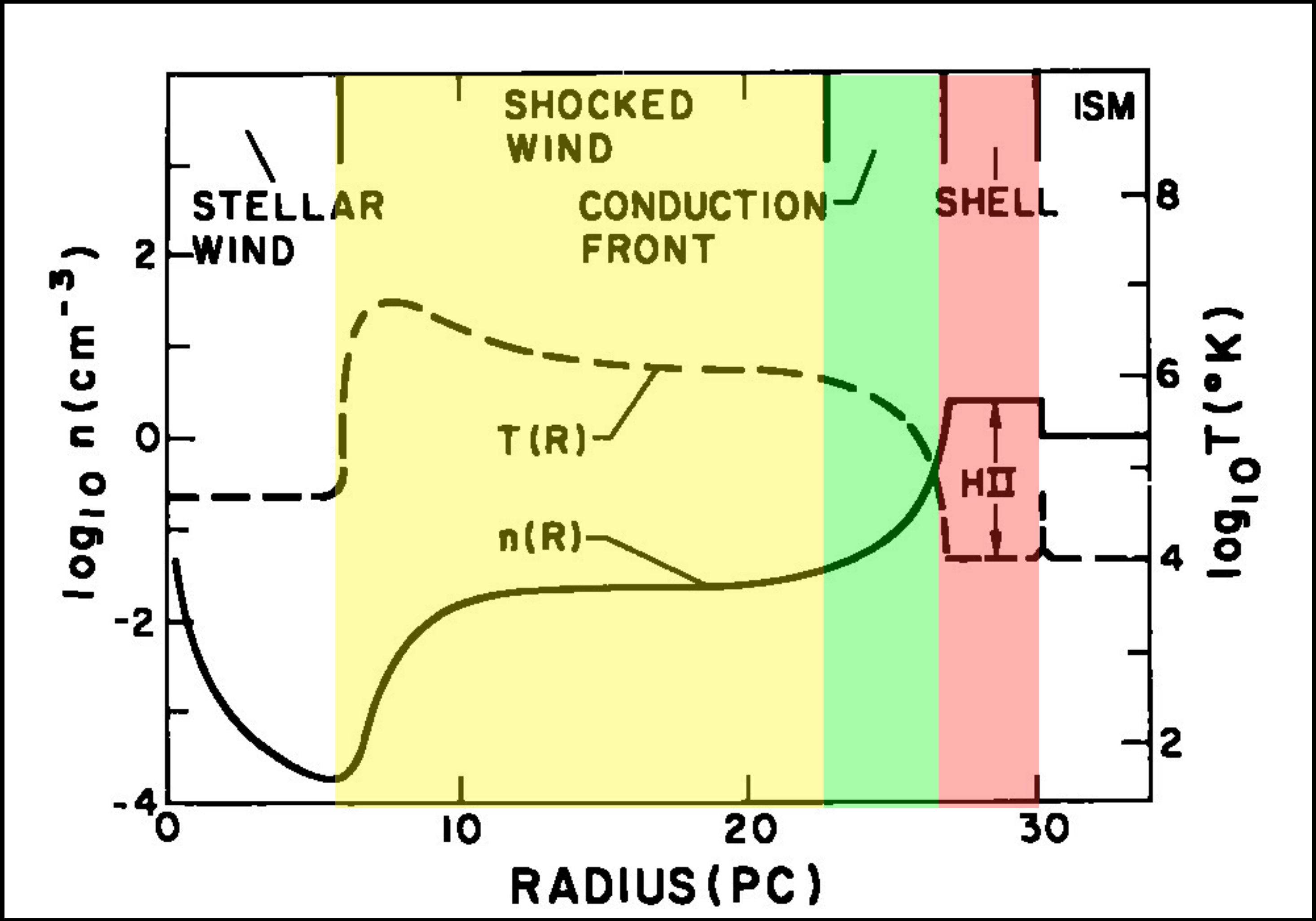
Low-mass ★ → RG, AGB → planetary neb.

Interstellar Bubble



Castor, McCray, Weaver 1975
Weaver et al. 1977

Schematic Bubble Structure



Weaver et al. 1977

Variations of Bubble Models

Superbubble Model

- intermittent SNe averaged over time ~ stellar wind
- blown out of galactic plane (Mac Low & McCray 1998)
- blown in magnetized medium (Tomisaka 1992)
- hot interior enriched with O and Fe (Silich et al. 2001)

Circumstellar Bubble Model

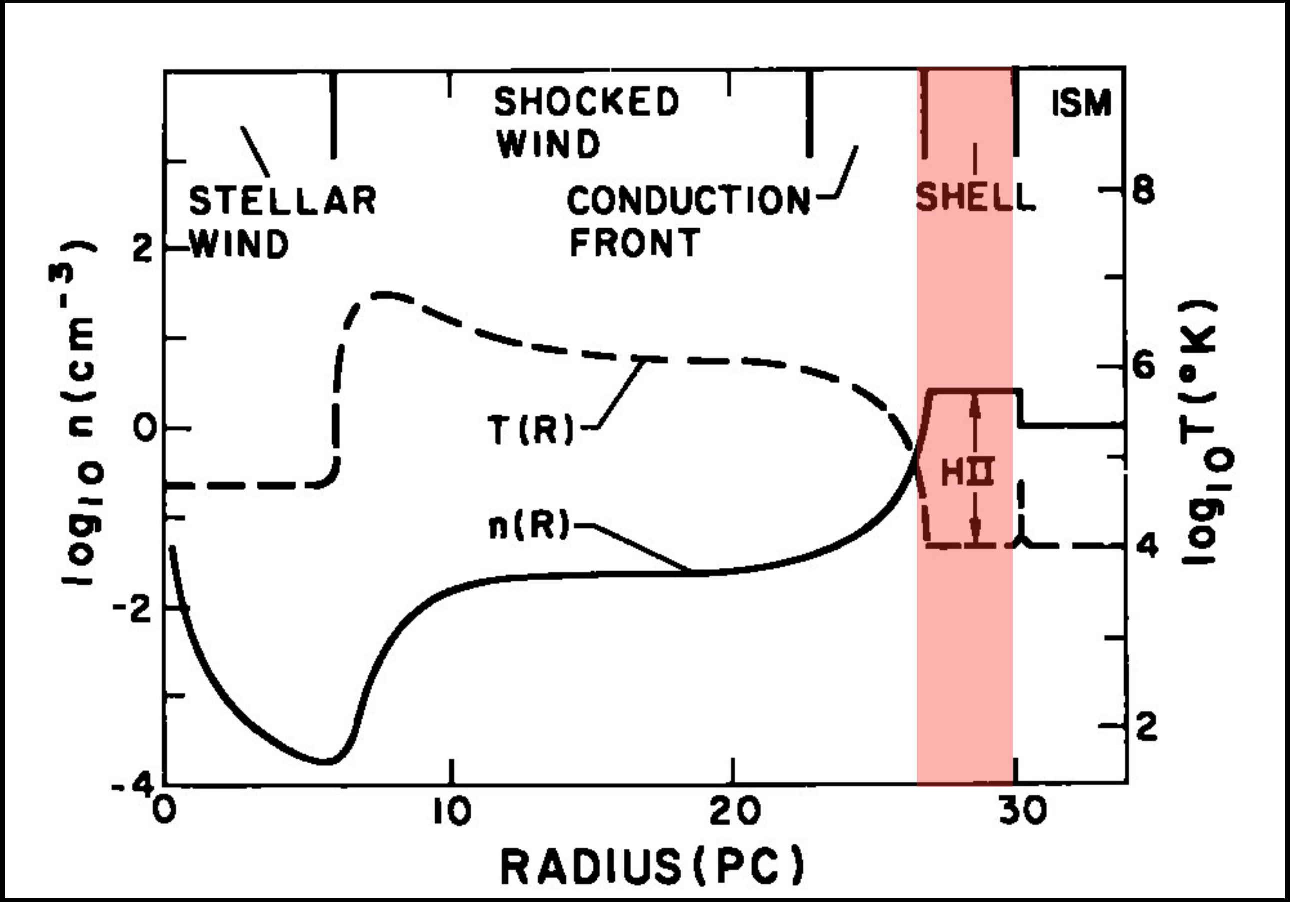
- ambient medium with density $\propto r^{-2}$
- wind velocity and mass loss rate are functions of time
- hydrodynamic model (García-Segura et al. 1996)
- radiative hydrodynamic model (Freyer et al. 2006)
- mass -loading by evaporation/ablation (Pittard et al. 2001)

Planetary Nebula model

- similar to circumstellar bubbles
- stellar radiation is a strong function of time
- Schönberner, Steffen, Warmuth 2006

Dense Swept-up Shell

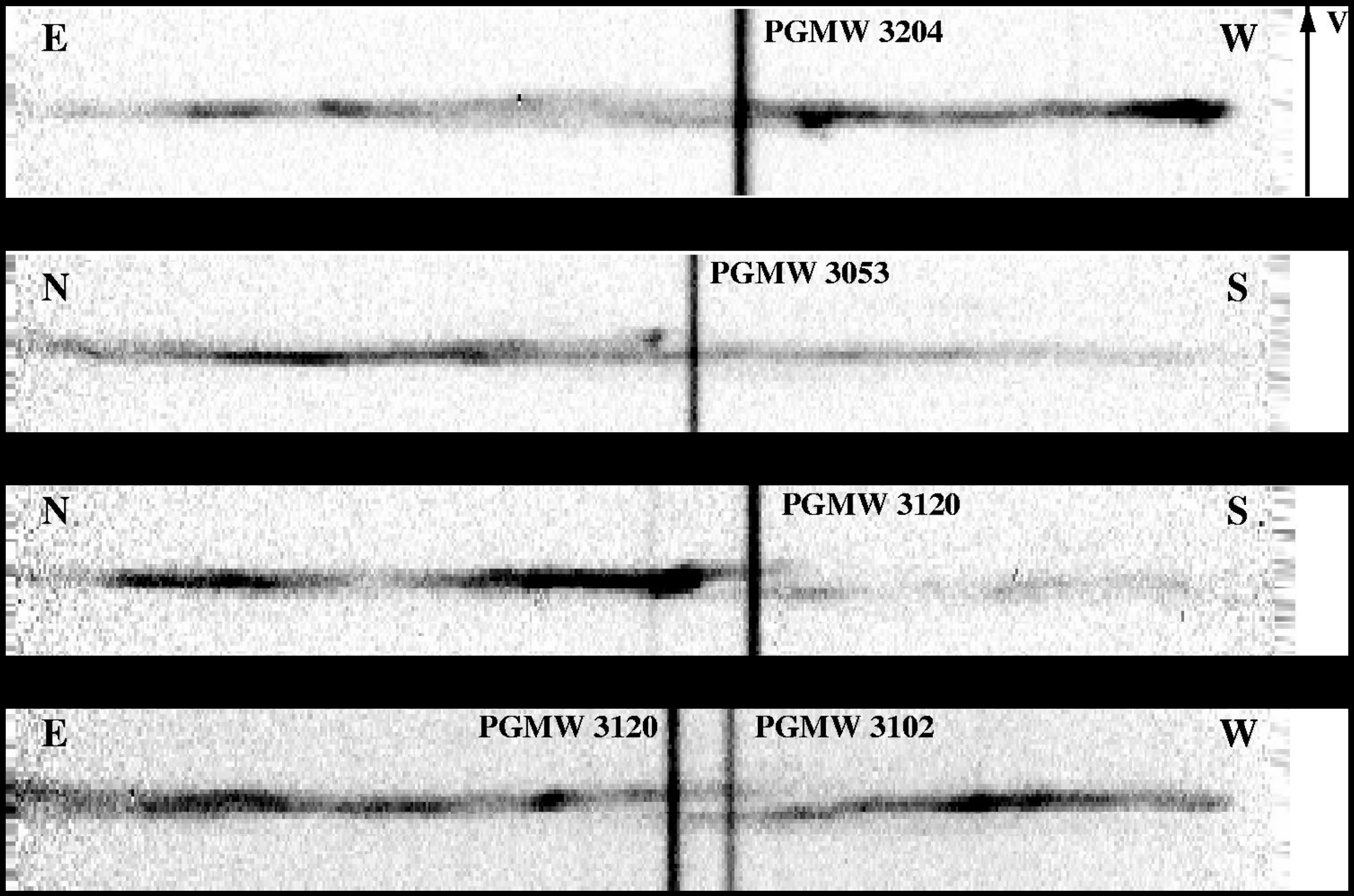
- Why don't we see more interstellar bubbles?



The Bubble Nebula

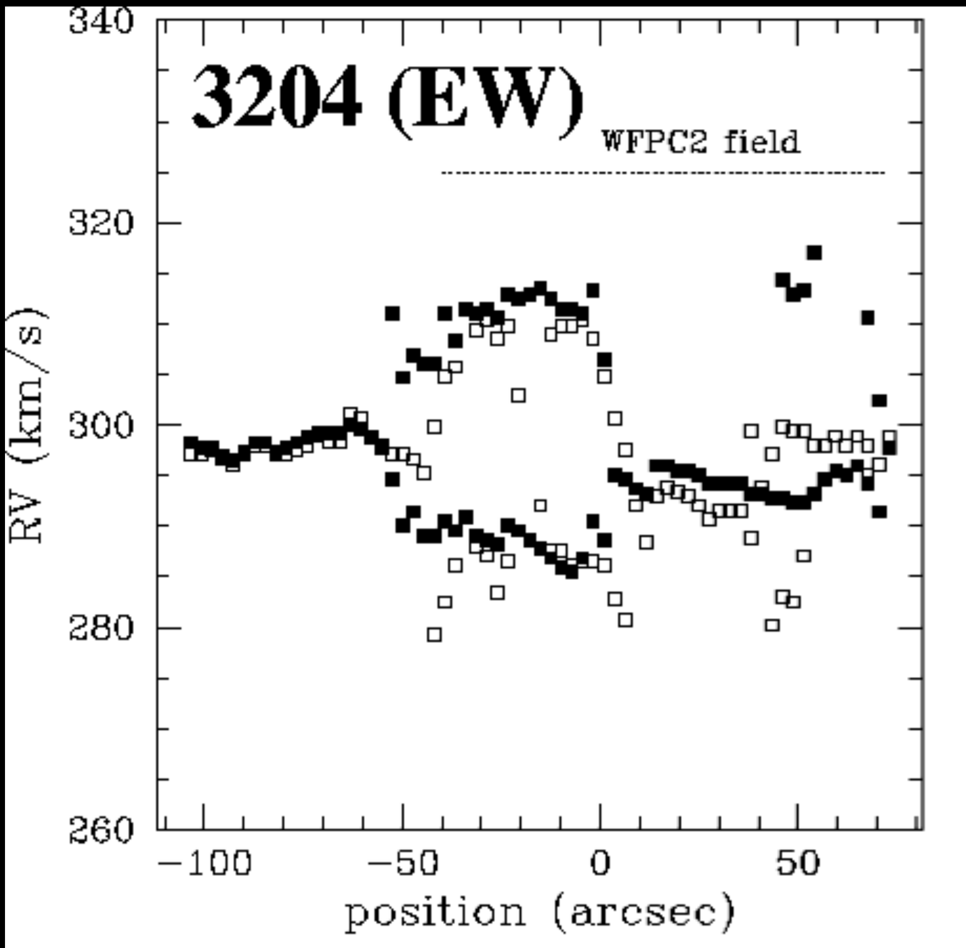
N11B - Young OB Association LH10

Echellogram of [N II] 6583 Line



Bubble Size ~ 15 pc

Exp Vel ~ 15-20 km/s



Naze, et al. 2001, AJ, 122, 921

Ionized shell (H II)

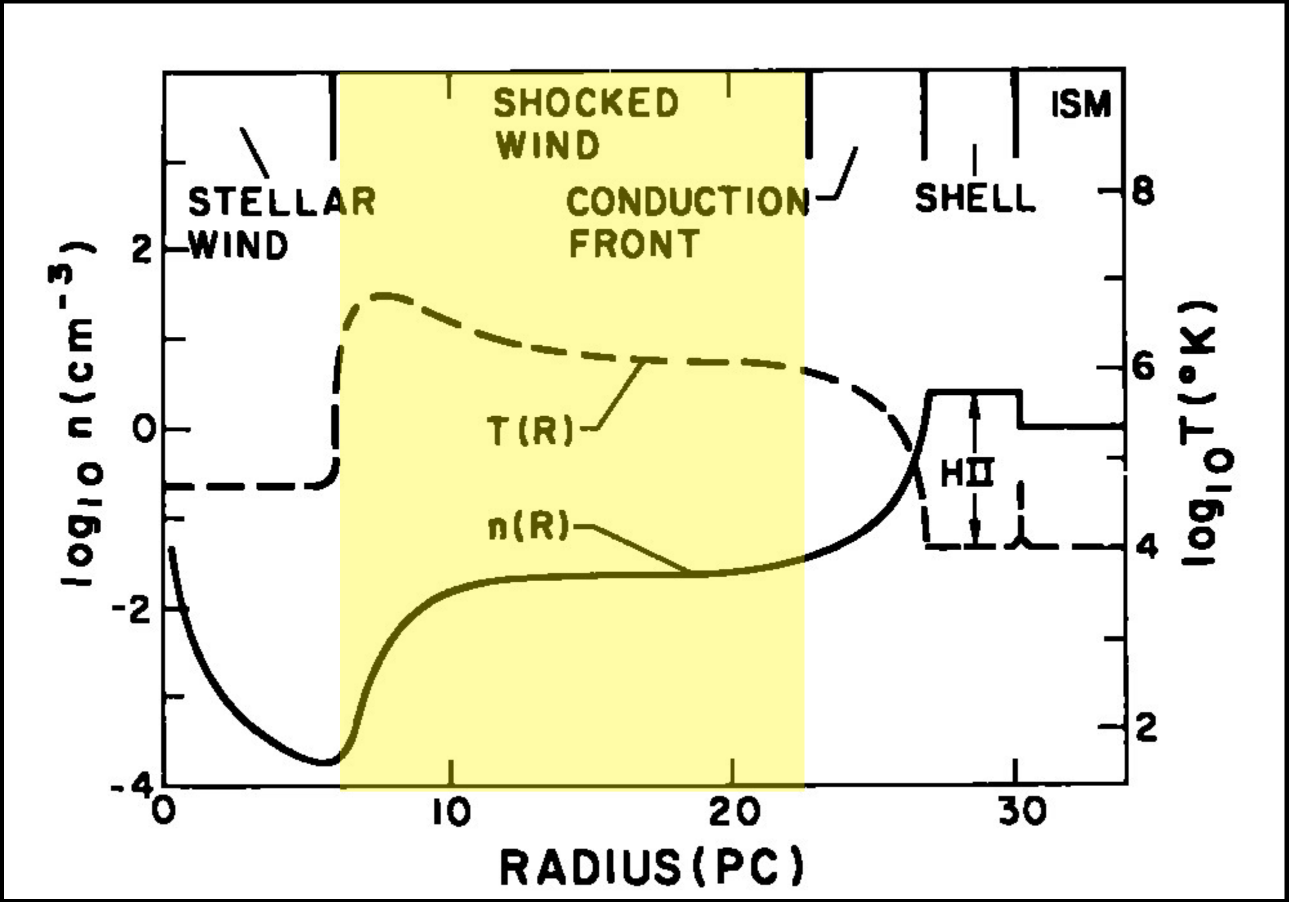
- **sound vel ~ 10 km/s**
- **no strong shocks**
- **no large density jump**
- **no limb-brightening**

Neutral shell (H I)

- sound vel ~ 1 km/s
- large density jump
- limb-brightening
- frequently seen

Hot Gas in Bubble Interiors

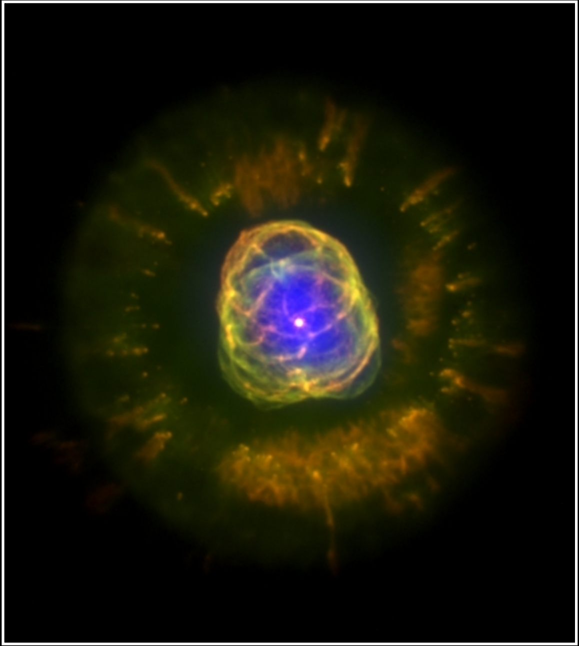
X-ray observations



Hot Gas in Planetary Nebulae

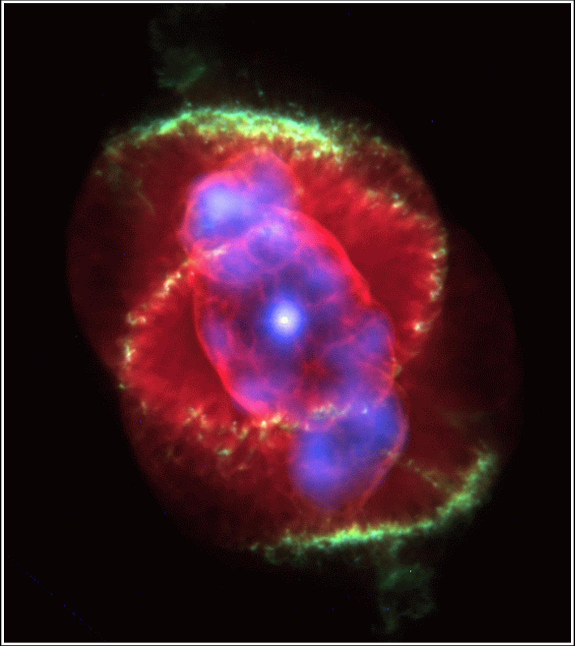
X-ray emission (blue) detected by Chandra & XMM

NGC 2392



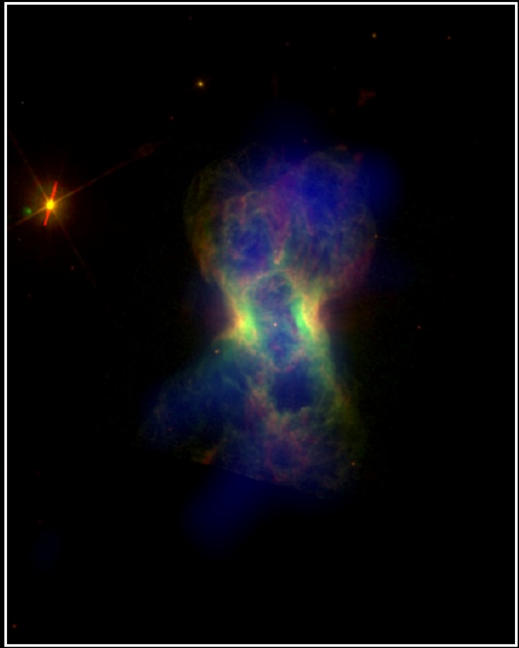
Guerrero et al. (2005)

NGC 6543



Chu et al. (2001)

NGC 7026



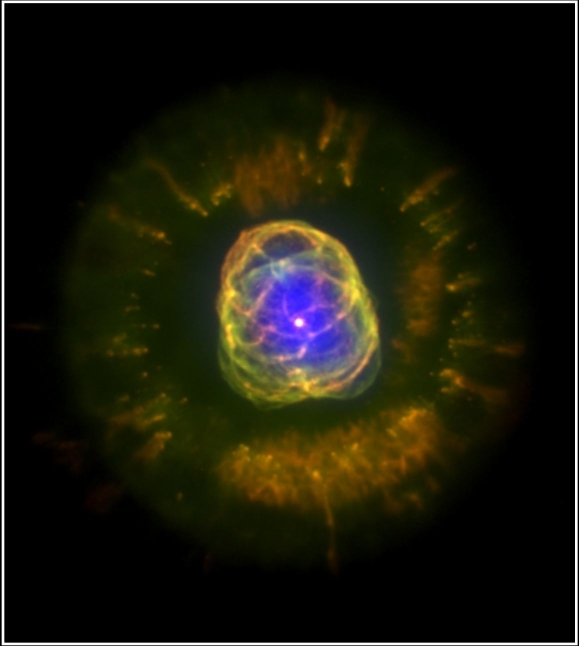
Gruendl et al. (2006)

Young PNe with closed inner shell or lobes; P Cygni stellar line profiles; low foreground absorption; 1-3 x 10^6 K.

Hot Gas in Planetary Nebulae

X-ray emission (blue) detected by Chandra & XMM

NGC 2392



Guerrero et al. (2005)

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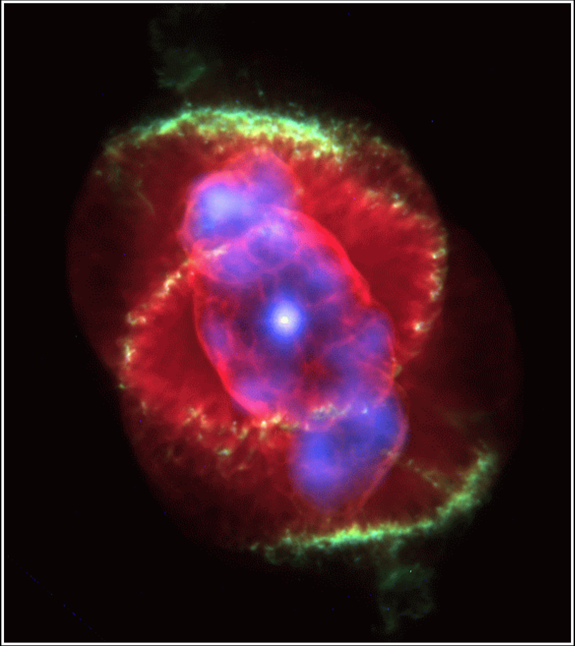

Chu et al. (2001)

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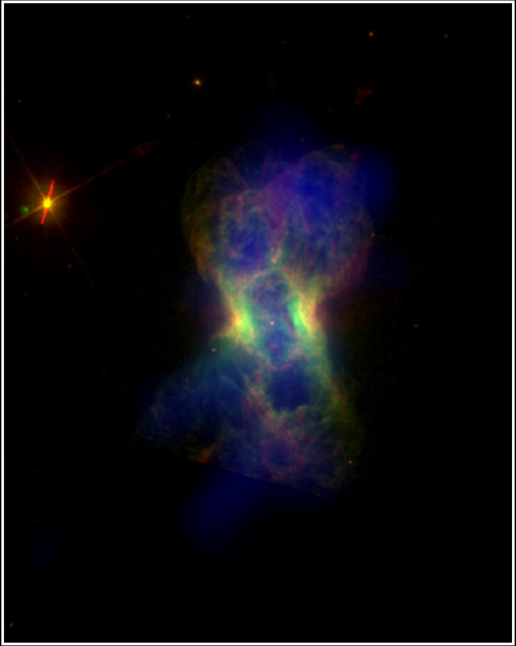
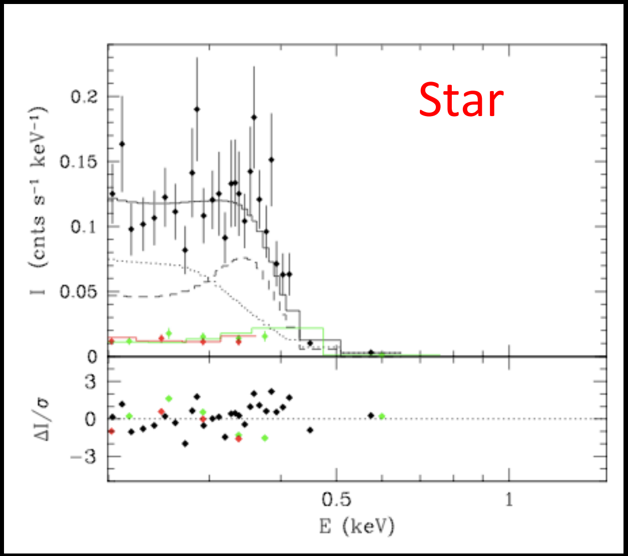


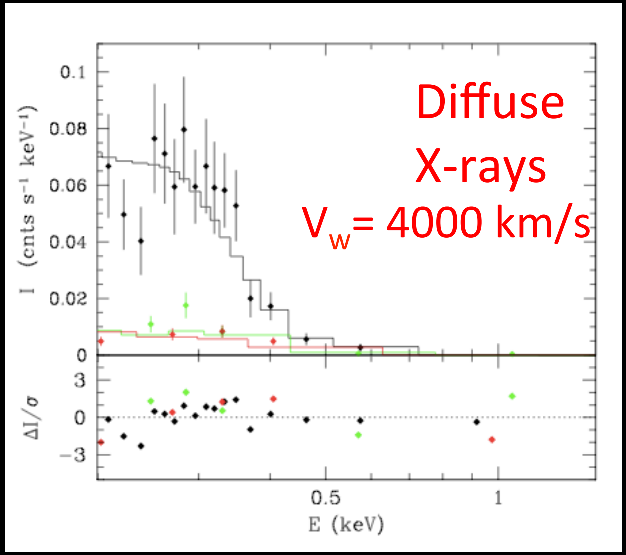
Gruendl et al. (2006)

NGC 2392 -- V_w = 300 km/s , $T = 2 \times 10^6$ K

NGC 6543 -- V_w = 1450 km/s , $T = 1.6 \times 10^6$ K

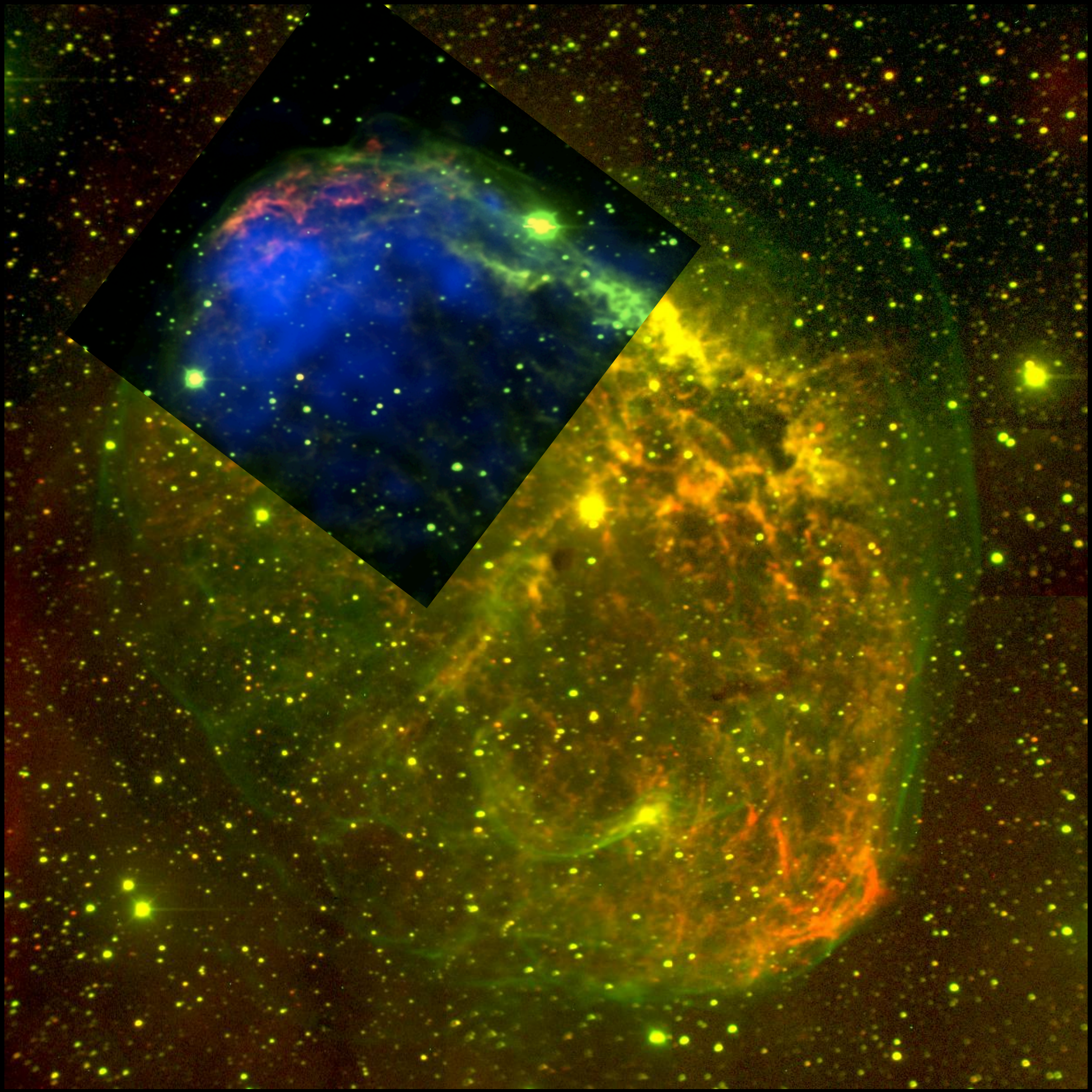
Hot Gas in the Born-Again PN A30





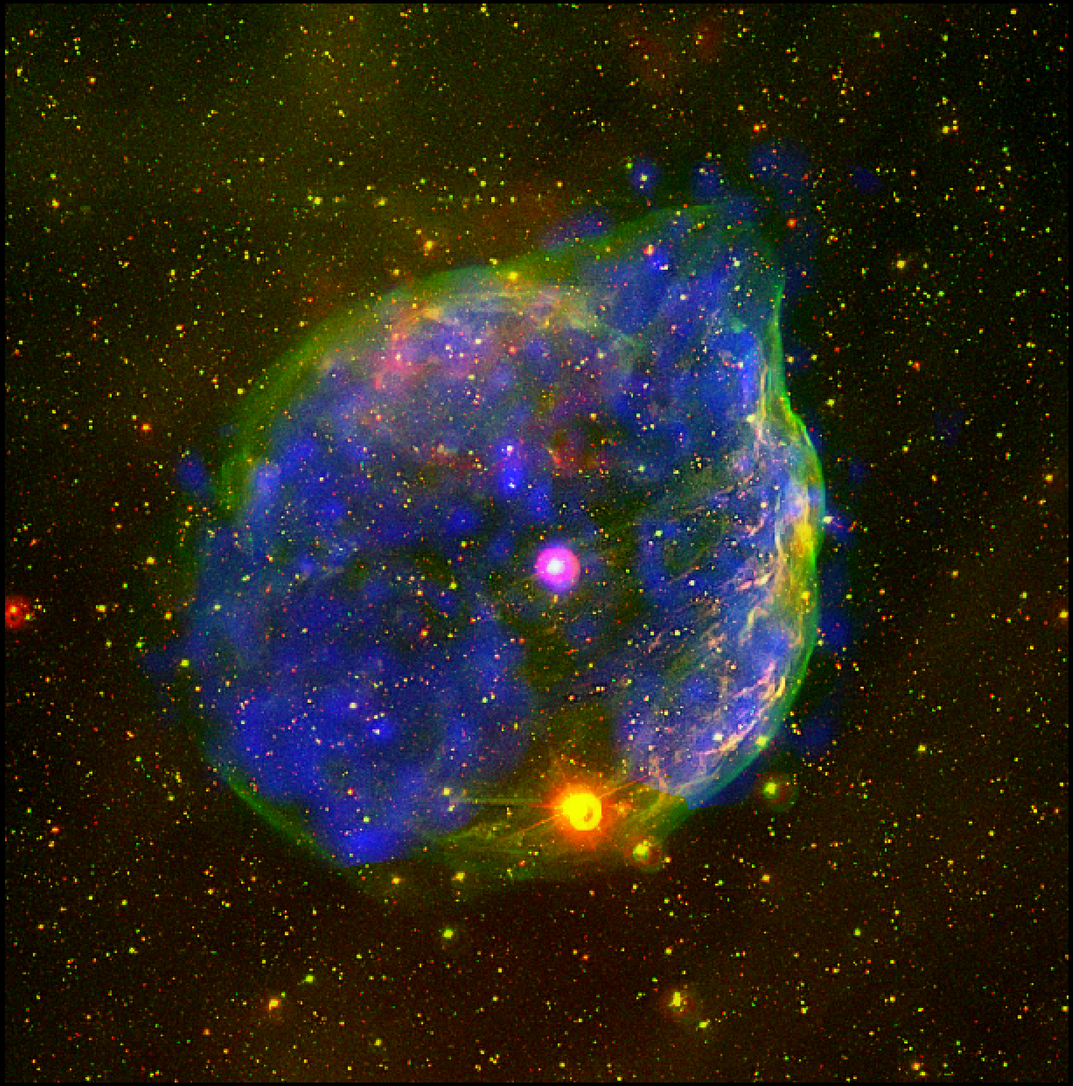
Guerrero et al. (2012)

Circumstellar Bubble NGC 6888



Toalá et al. (2013, in prep)

Circumstellar Bubble S308



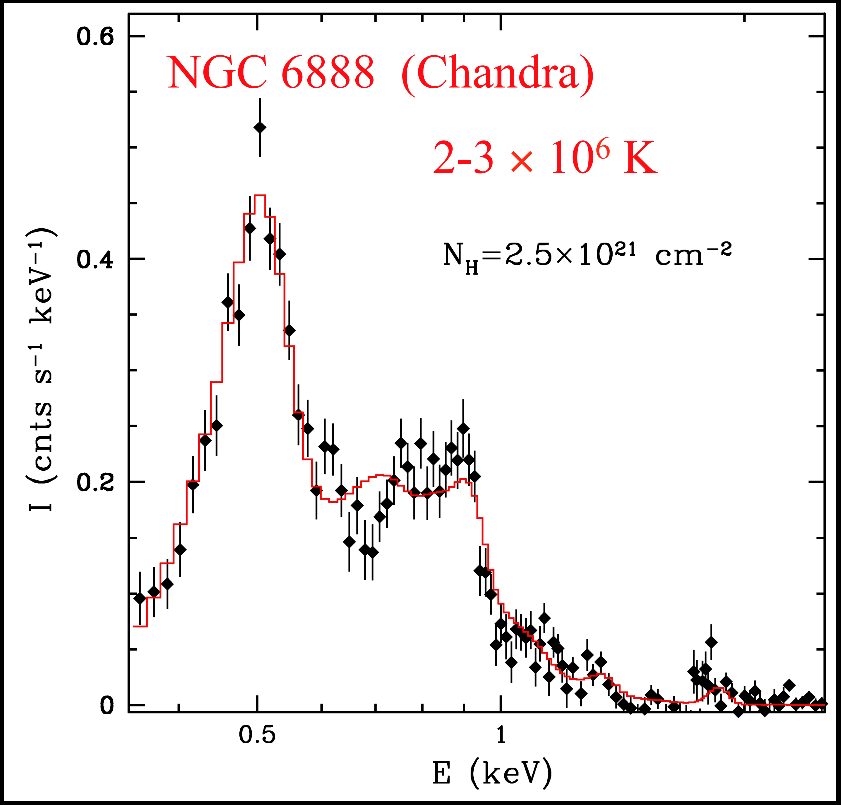
Red: Hα
Green: [O III]
Blue: X-ray

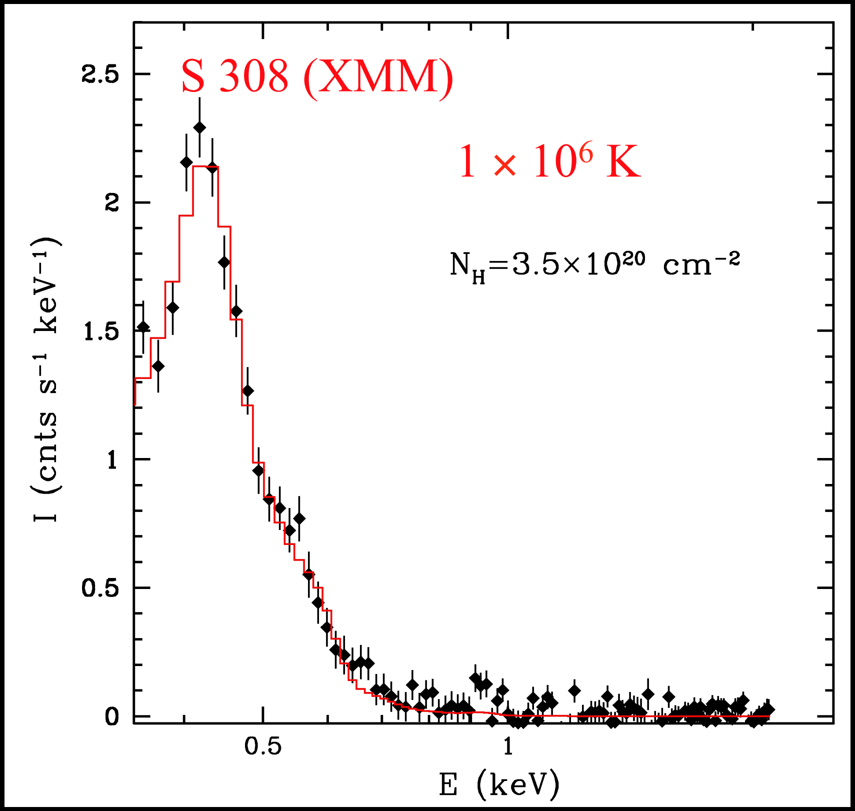
Chu et al. (2003); Toalá et al. (2012)

Hot Gas in Circumstellar Bubbles

The low temperatures can be achieved by thermal conduction, mass-loading, etc.

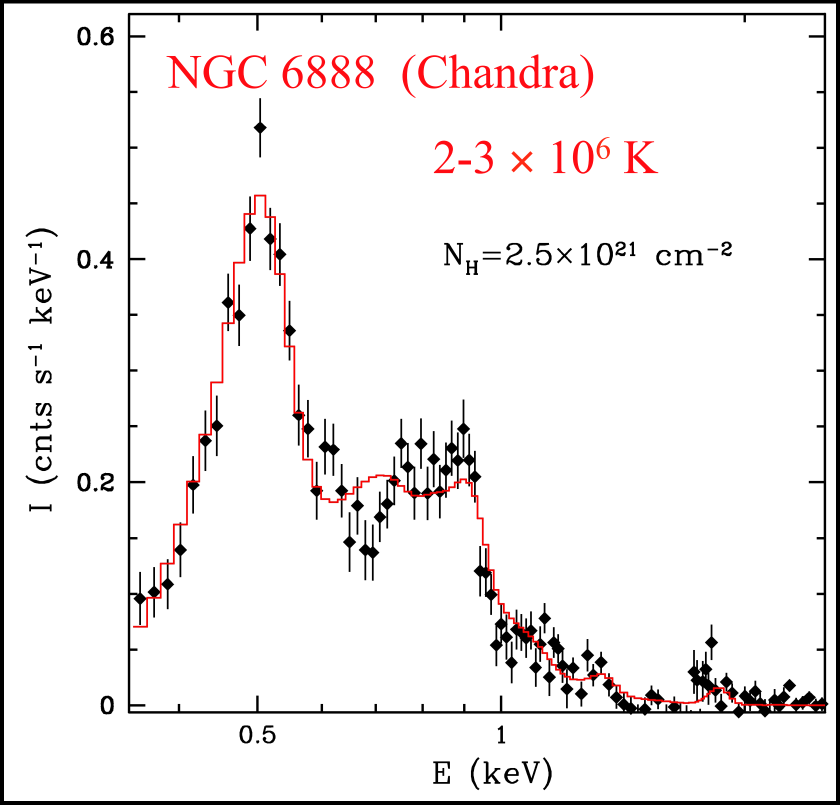
Soft X-rays can be absorbed => few bubbles detected

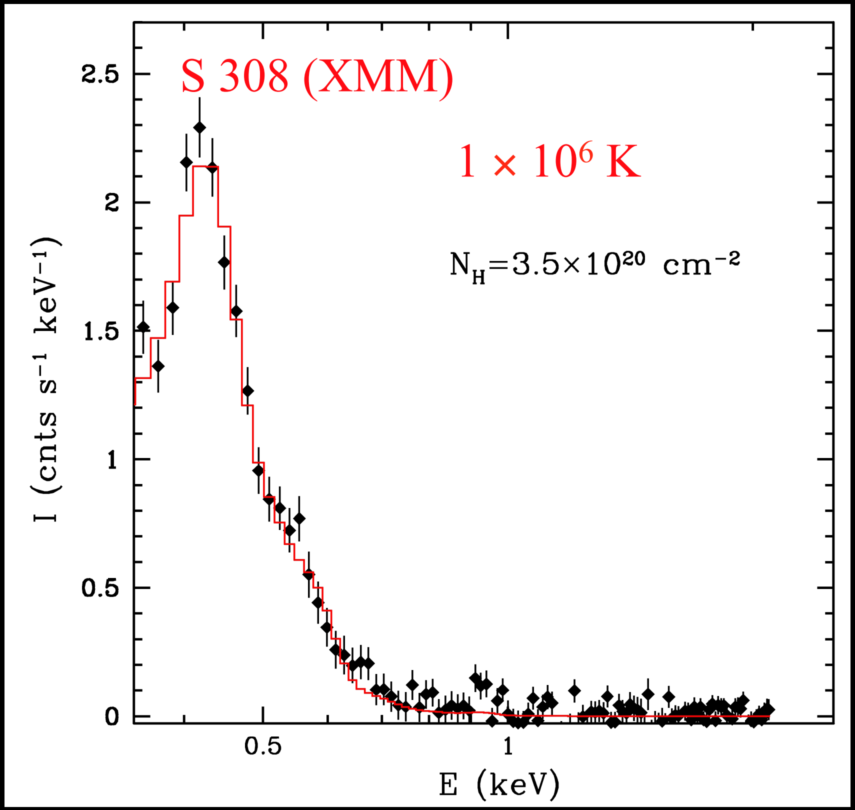




Hot Gas in Circumstellar Bubbles

However, the hot, shocked winds should have been detected. The absence of hotter gas is puzzling. (Arthur 2012)



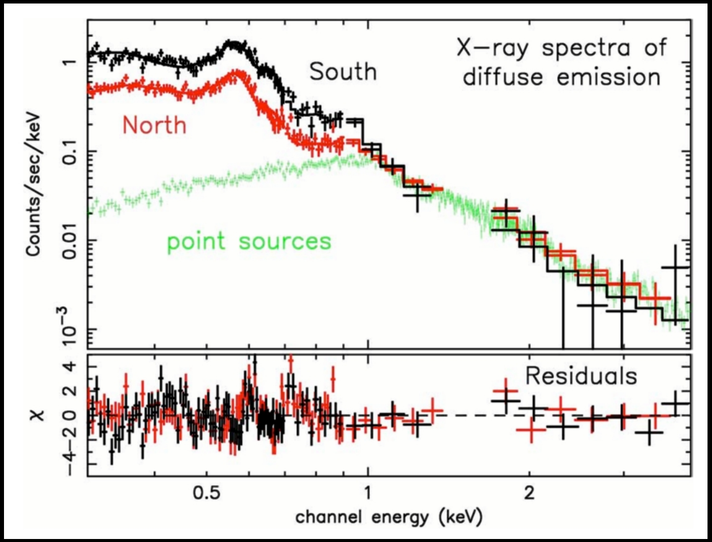


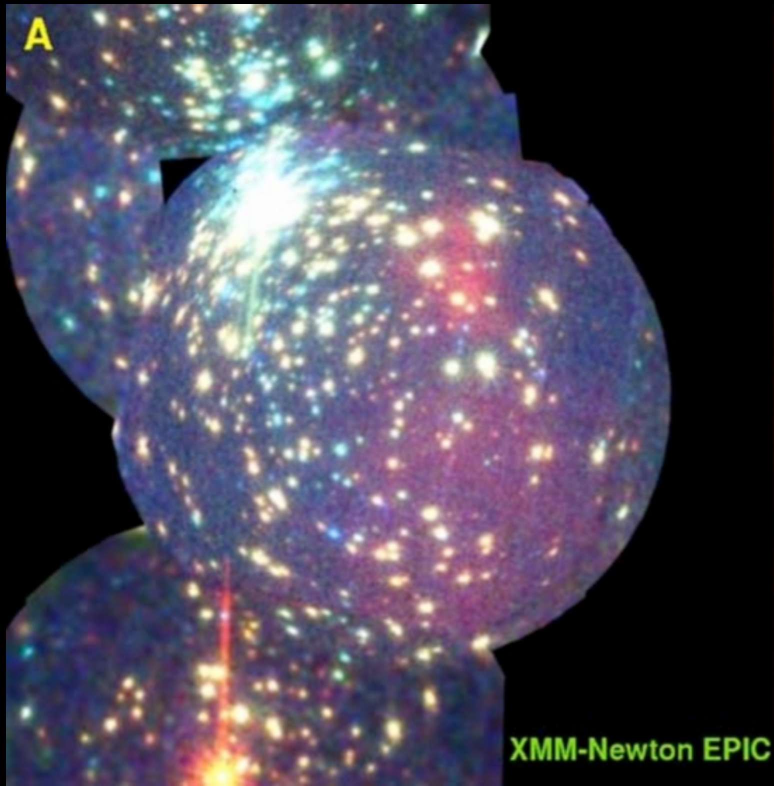
Hot Gas in the Orion Nebula

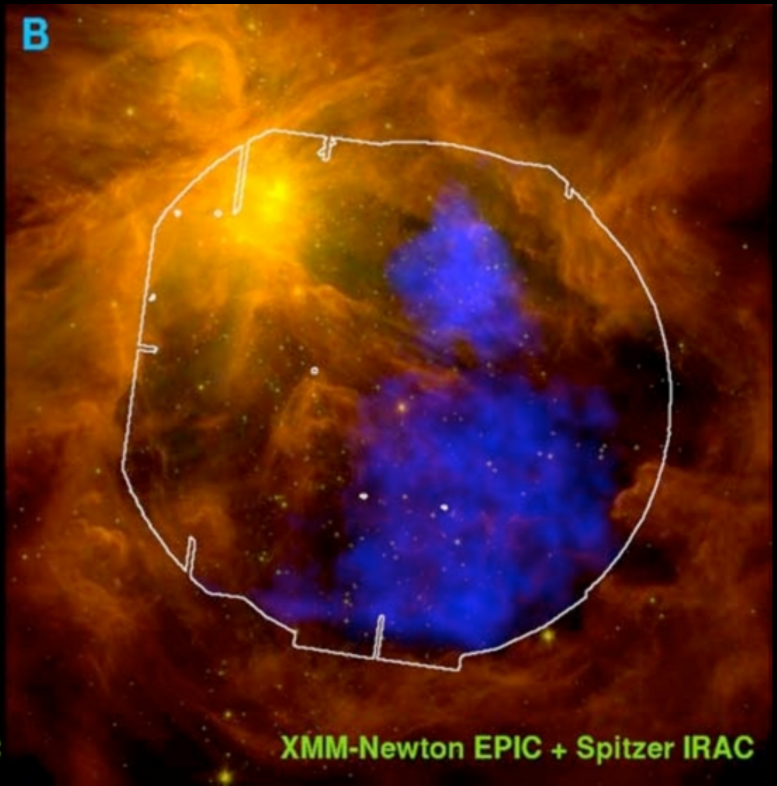
$T \sim 2 \times 10^6$ K

$Lx \sim 5.5 \times 10^{31}$ erg/s

(Güdel et al. 2008)





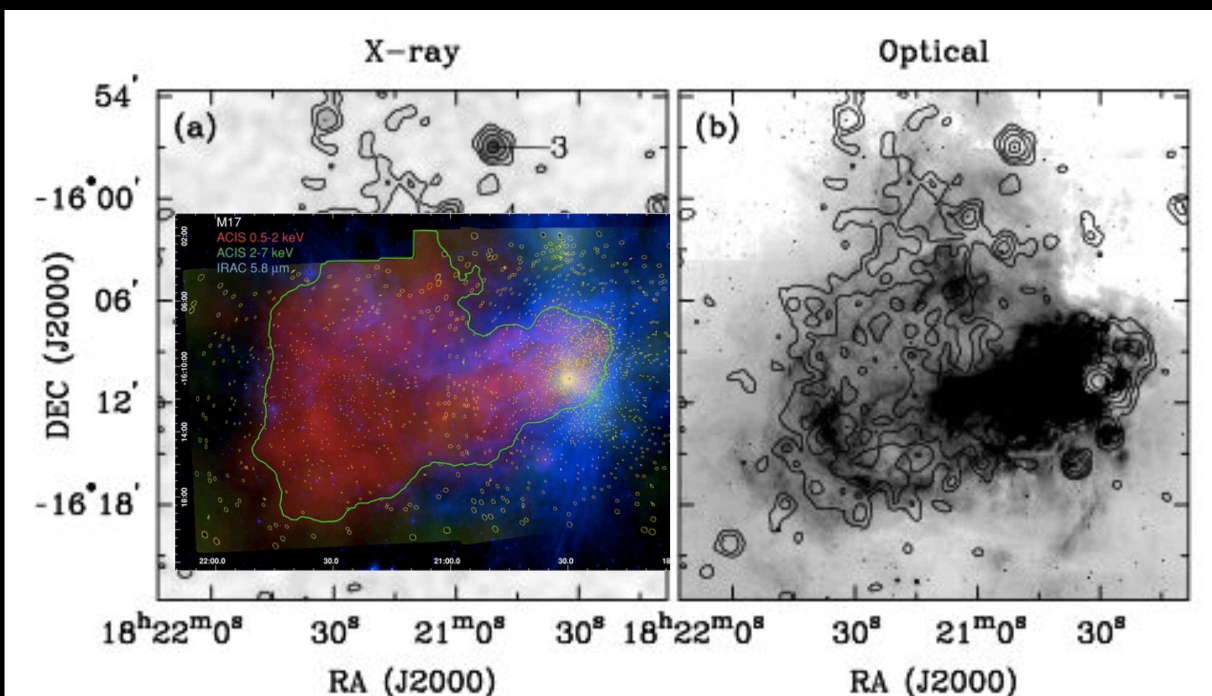


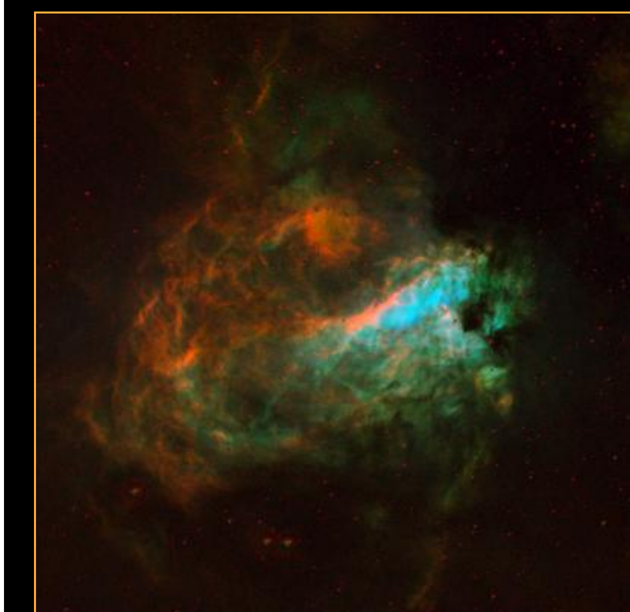
Hot Gas in the Omega Superbubble

Two young superbubbles are detected in X-rays by Chandra: Omega and (Rosette)

ROSAT - Dunne et al. 2003

Chandra - Townsley et al. 2003





Hot Gas in Wind-blown Bubbles

- Detection of hot gas associated with fast winds
  - 12 PNe, 2 WR bubbles, 2 superbubbles*

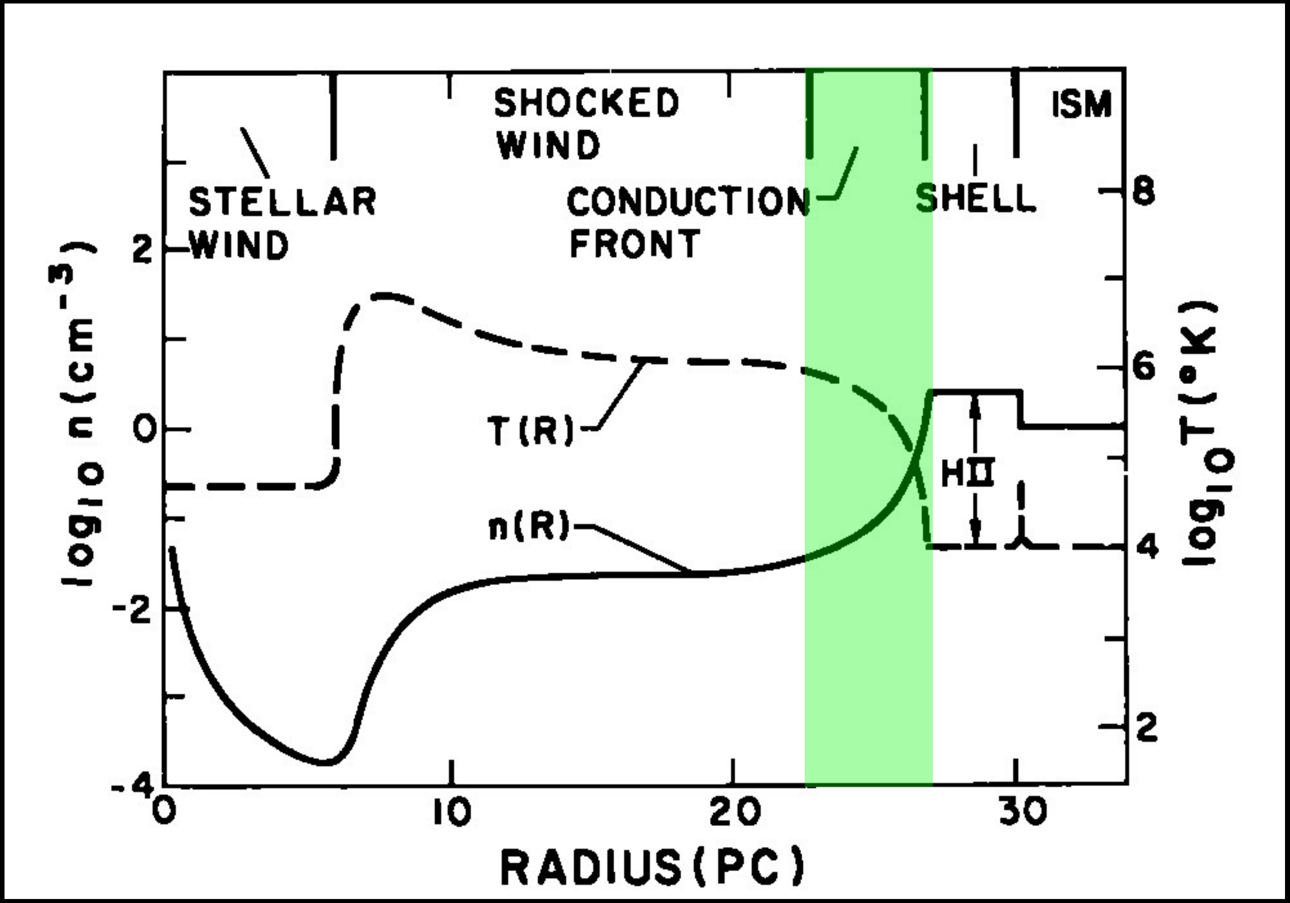
    (* Townsley et al. 2003; Güdel et al. 2008)

- Properties of the hot gas:

	T_e [10^6 K]	N_e [cm^{-3}]	L_X [erg/s]
PN	$1\text{-}3 \times 10^6$	100	10^{31} - 10^{32}
WR	$1\text{-}2 \times 10^6$	1	10^{33} - 10^{34}
M17	7×10^6	0.3	10^{33}
Orion	2×10^6	0.2-0.5	5×10^{31}

Conduction Layer in Bubbles

- Probe the thermal conduction layer using high ions produced by thermal collisions



O VI

N V

C IV

Si IV

Ionization Potentials (in eV)

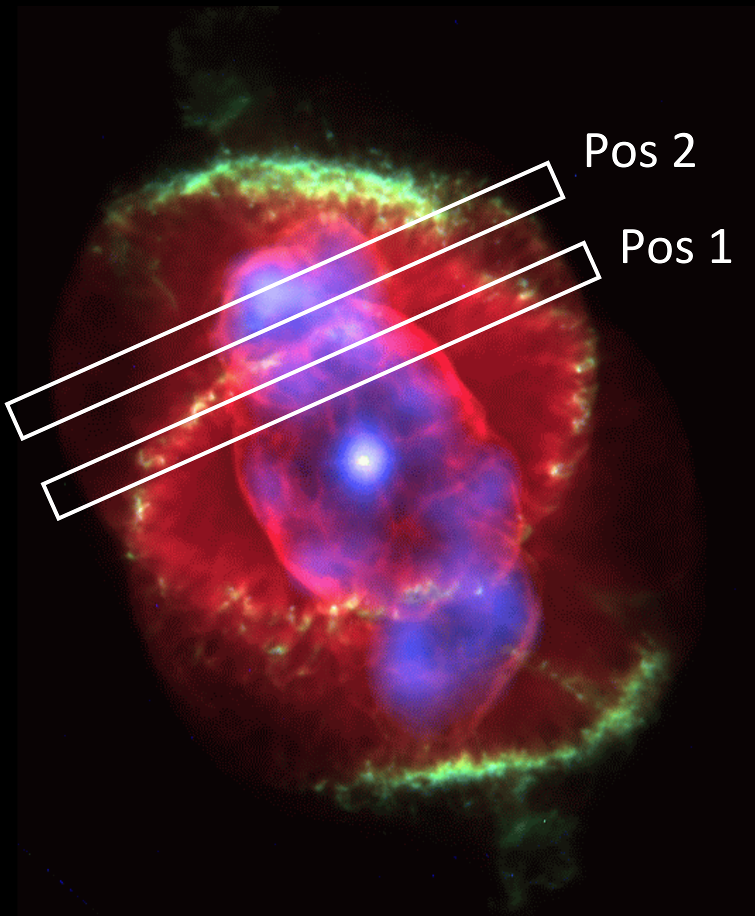
Excitation potential of O VI
= Ionization potential of O V

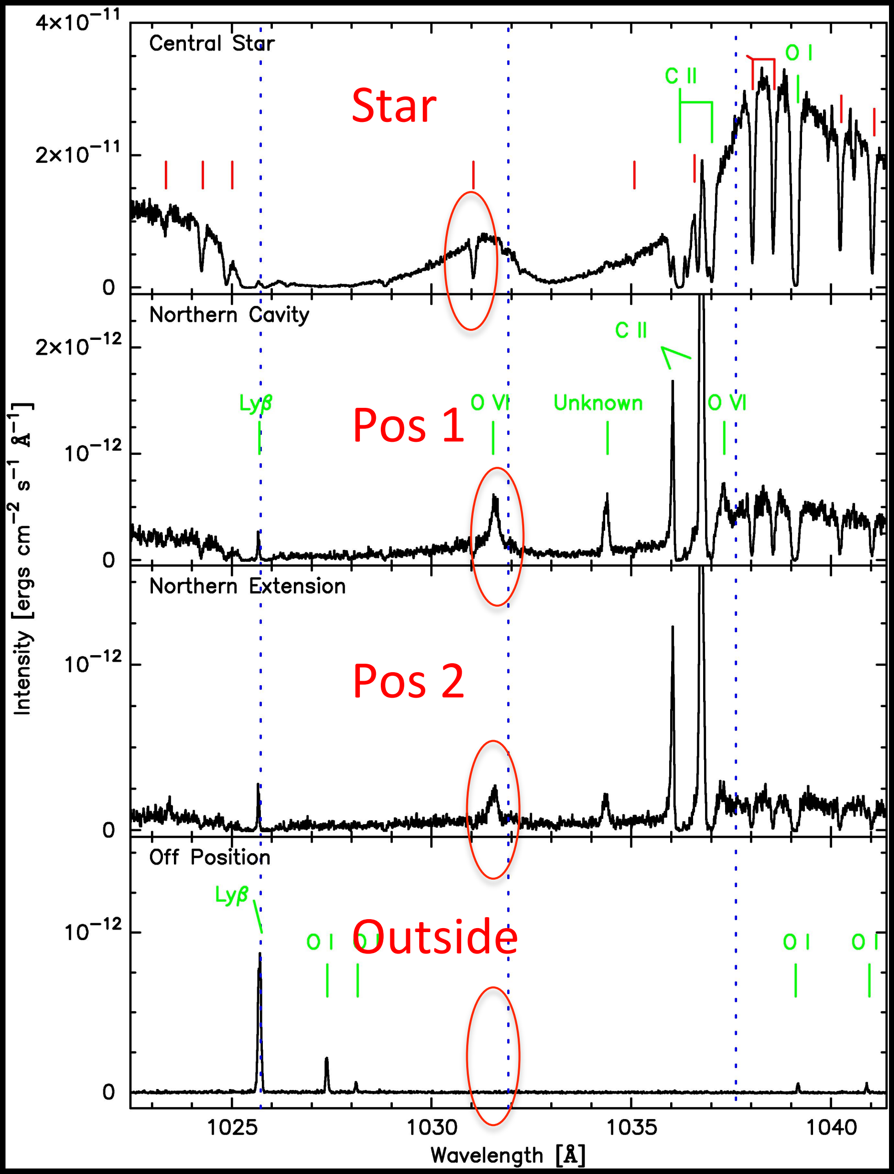
$3kT/2$ = 129 eV
for $T = 10^6$ K

	Atom	I	II	III	IV	V	VI
1	H	13.598 44					
2	He	24.587 41	54.417 78				
3	Li	5.391 72	75.640 18	122.454			
4	Be	9.322 63	18.211 16	153.897	217.713		
5	B	8.298 03	25.154 84	37.931	259.366	340.22	
6	C	11.260 30	24.383 32	47.888	64.492	392.08	489.98
7	N	14.534 14	29.601 3	47.449	77.472	97.89	552.06
8	O	13.618 06	35.117 30	54.936	77.413	113.90	138.12
9	F	17.422 82	34.970 82	62.708	87.140	114.24	157.17

C IV 1548,1550; N V 1238,1240; O VI 1031,1037

FUSE Observations of O VI in NGC 6543

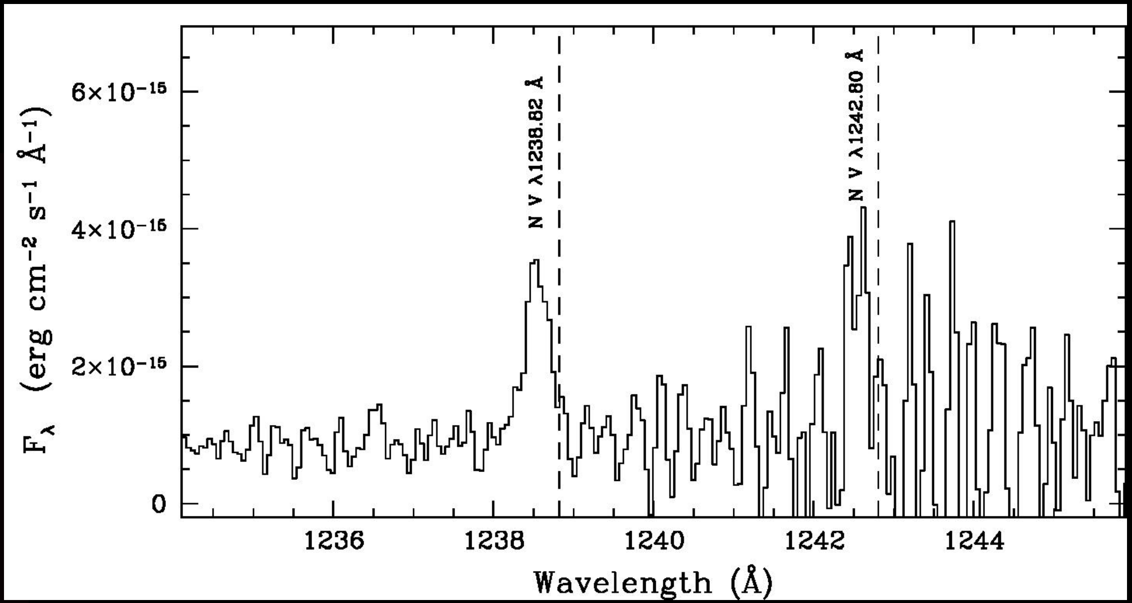


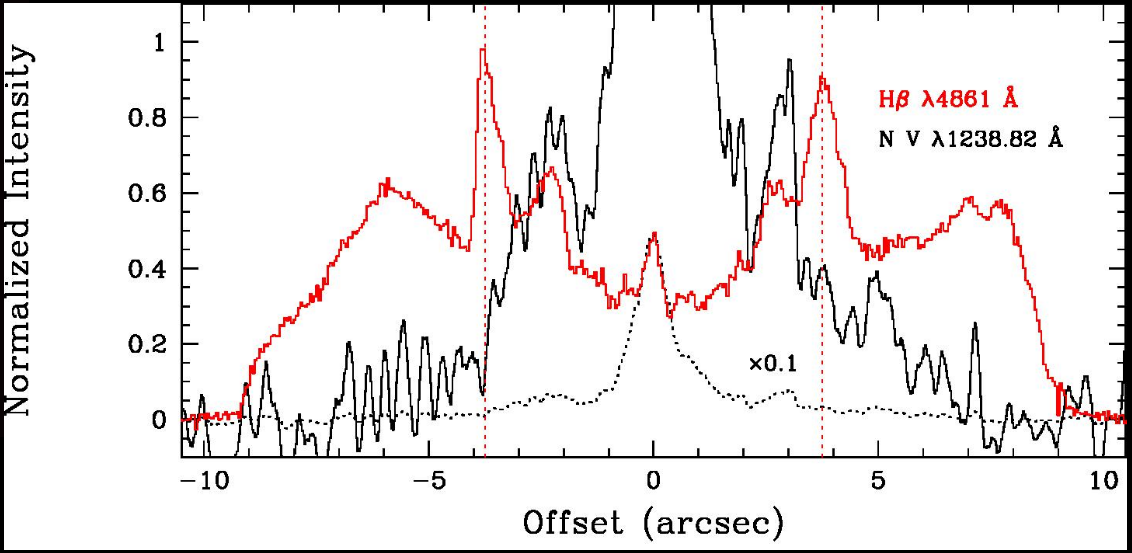


$$I_{\mathrm{O\,VI}} = n_{\mathrm{e}}\, n_{\mathrm{O\,VI}}\, h\nu\, \frac{8.629\times10^{-6}}{T^{1/2}} \frac{\bar{\Omega}_{\mathrm{O\,VI}}(T)}{g_j}\, e^{-\chi/kT} \frac{V}{4\pi d^2}$$

HST STIS Obs of N V in NGC 6543

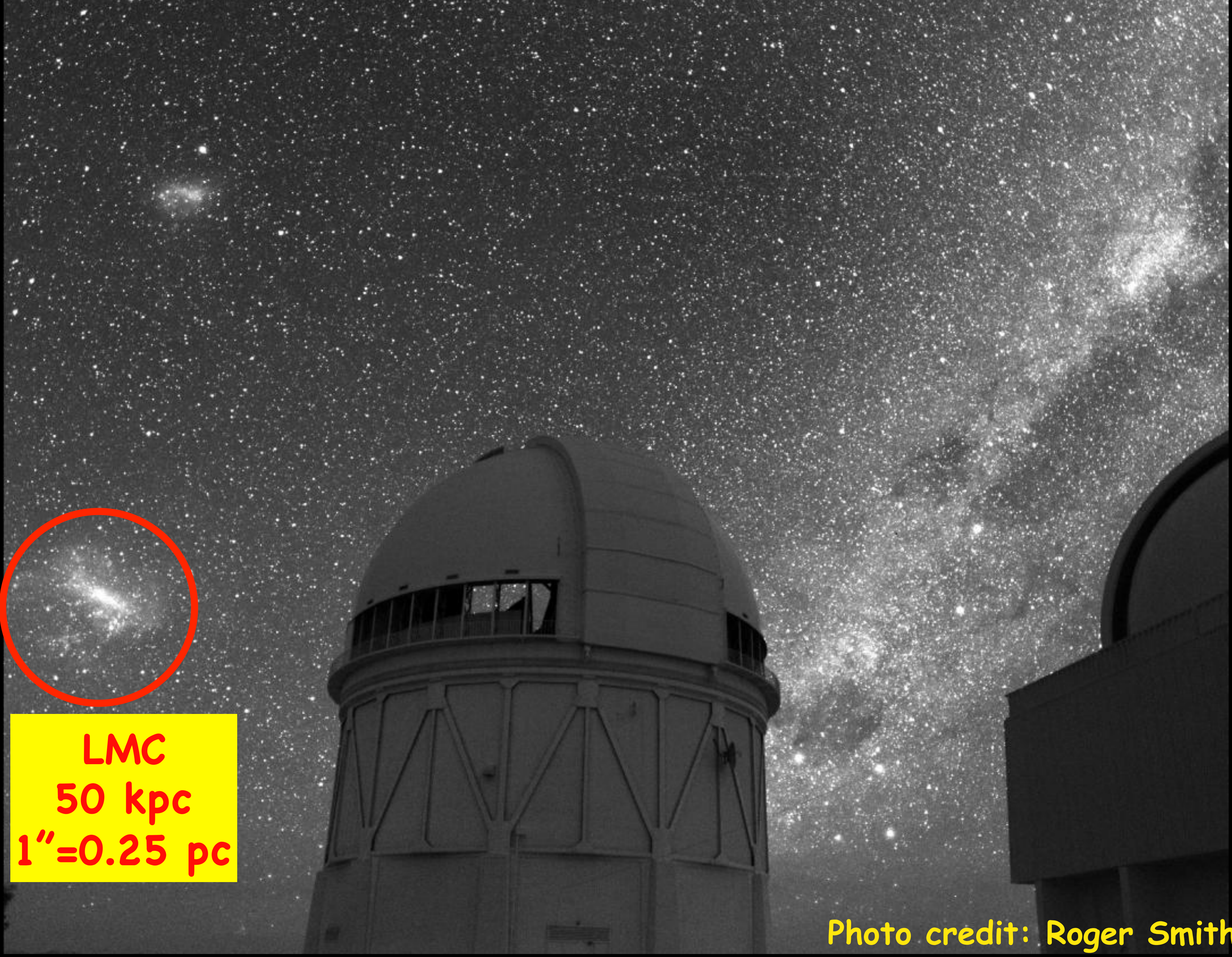
Long-slit spectra





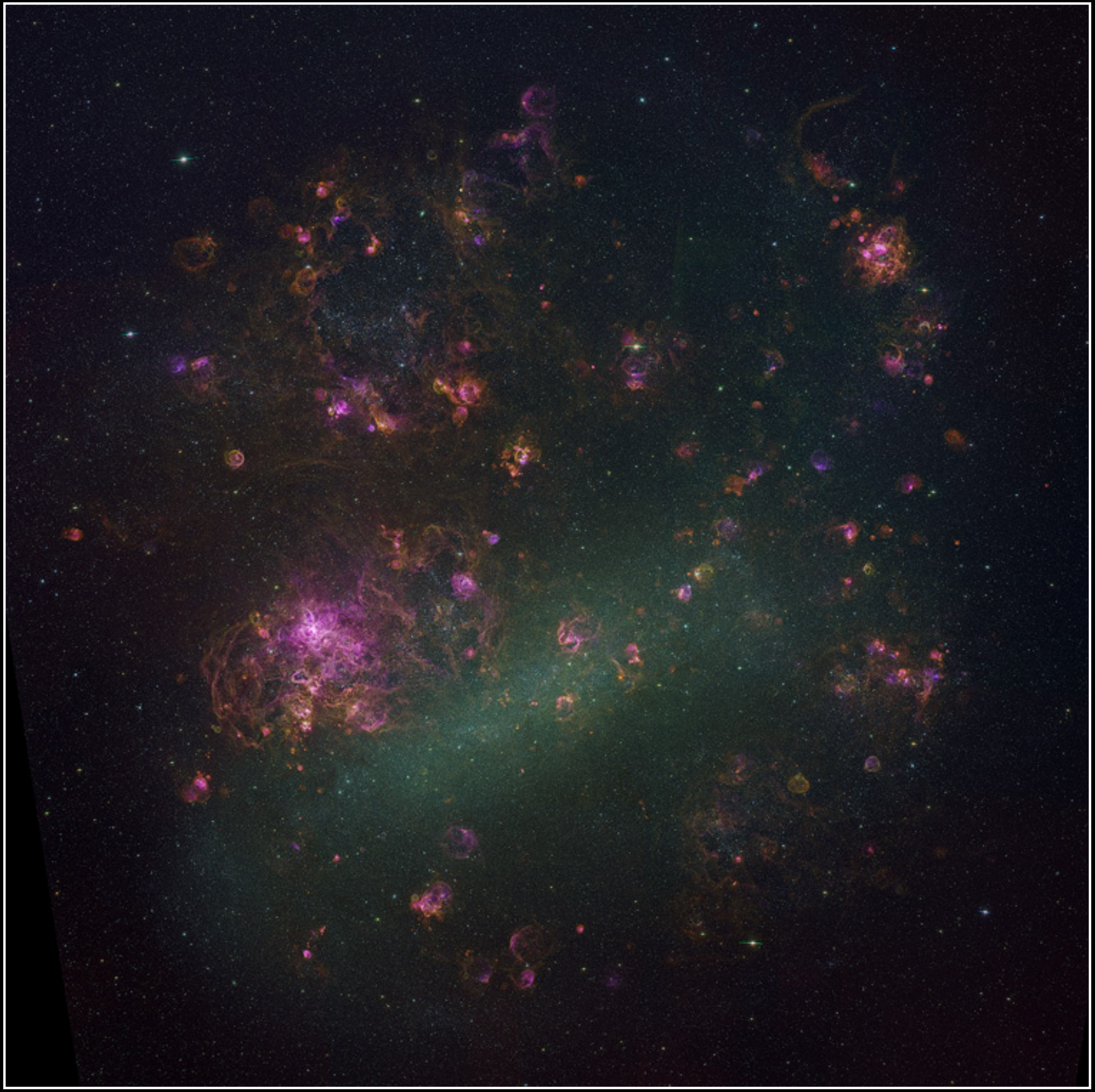
Guerrero et al. In prep

Best Galaxy to Study Supershells


LMC
50 kpc
1”=0.25 pc
Photo credit: Roger Smith

The Large Magellanic Cloud

MCELS (Hα, [O III], [S II])



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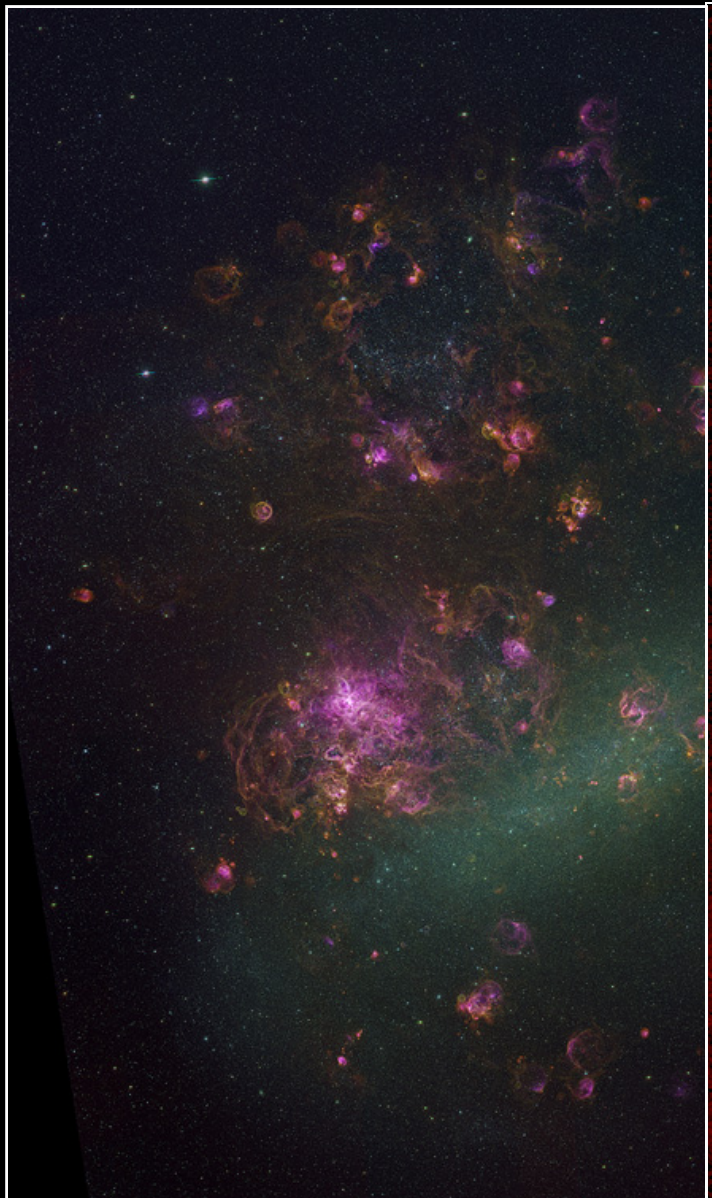
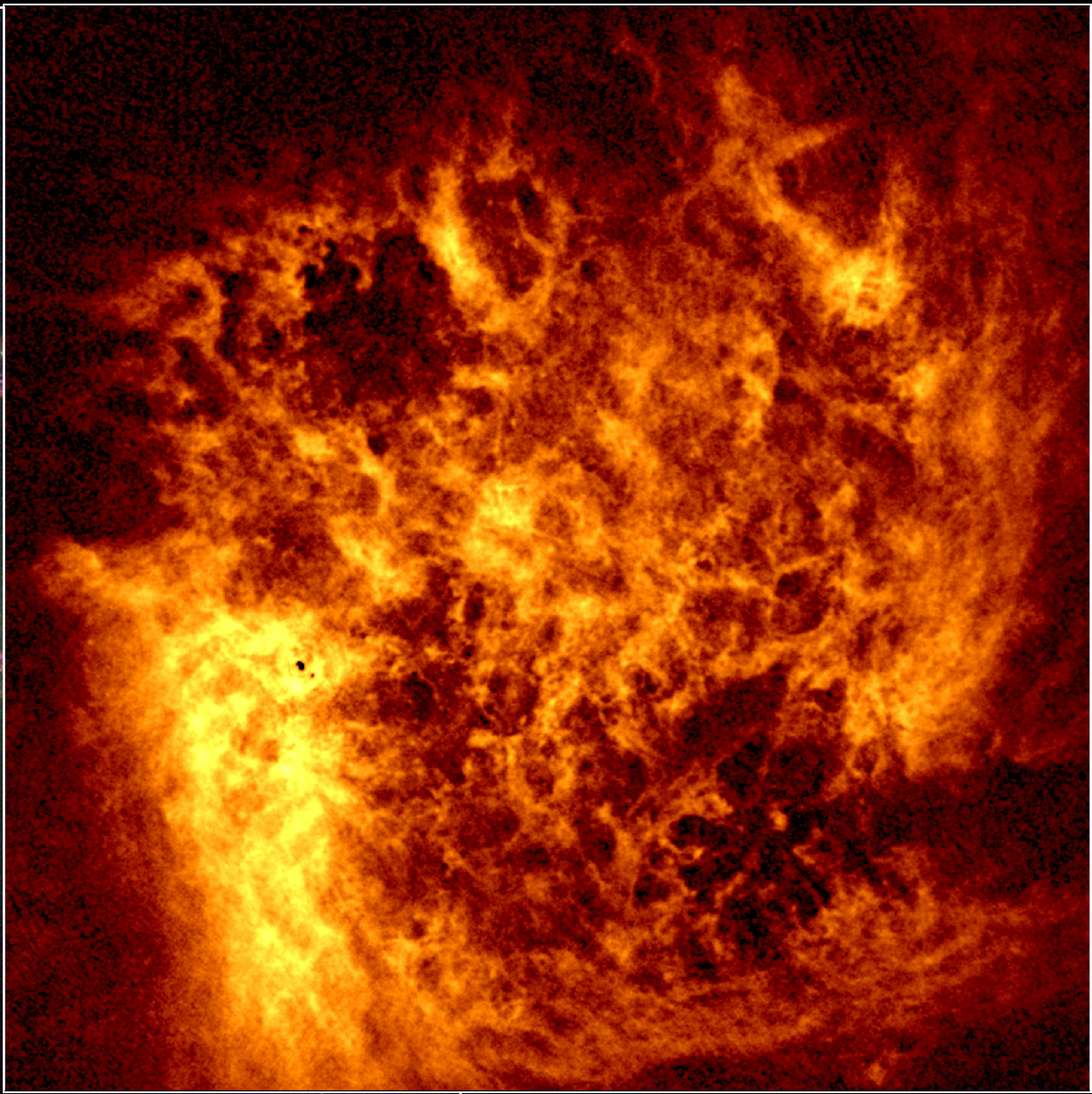
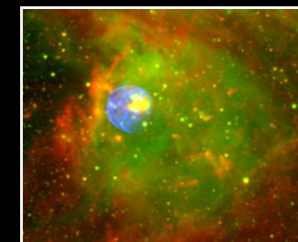


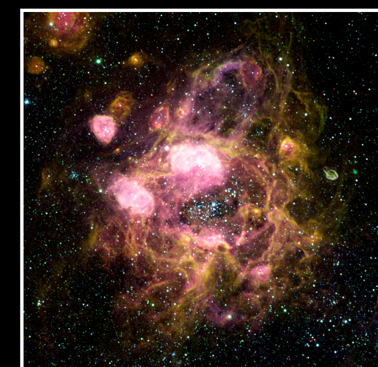
ATCA+Parkes (H I)

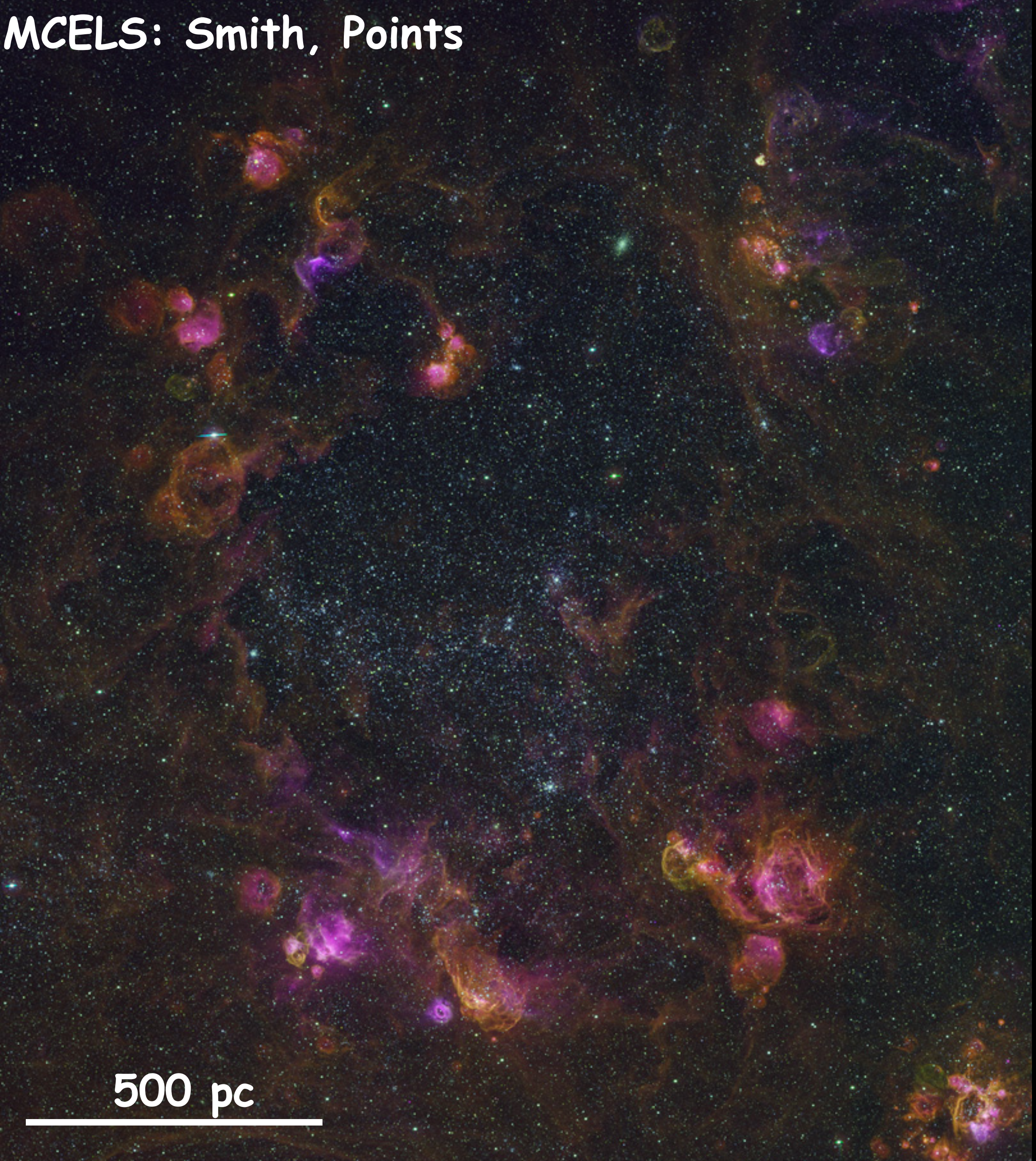


Evolution of Stars and ISM

Timeline	Star/SN	ISM	
2-3 Myr		HII region	
5 Myr	O -> SN	superbubble	
10 Myr	B -> SN	recombining	
>15 Myr		HI shell (10^2 pc)	SGS (10^3 pc)





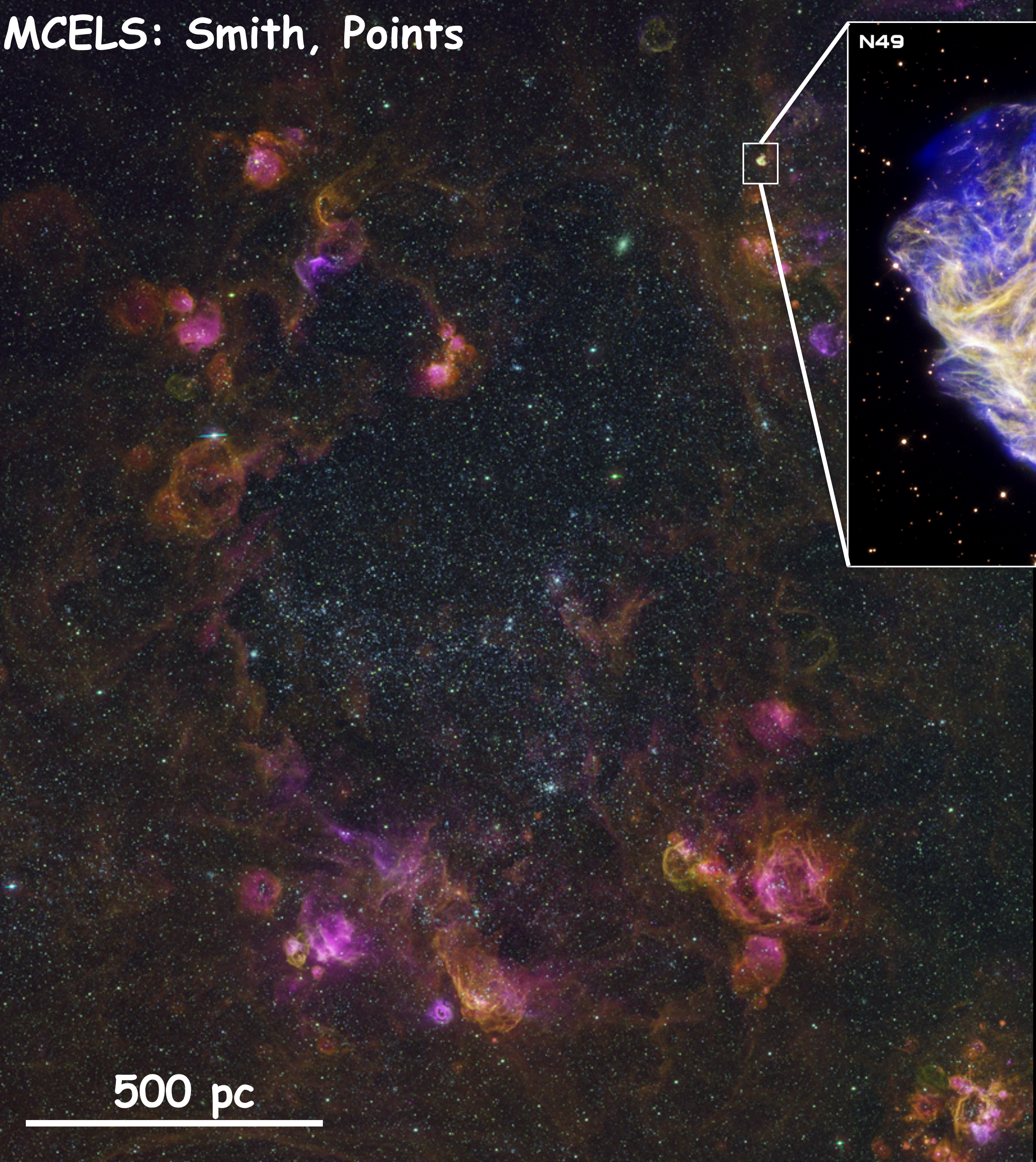


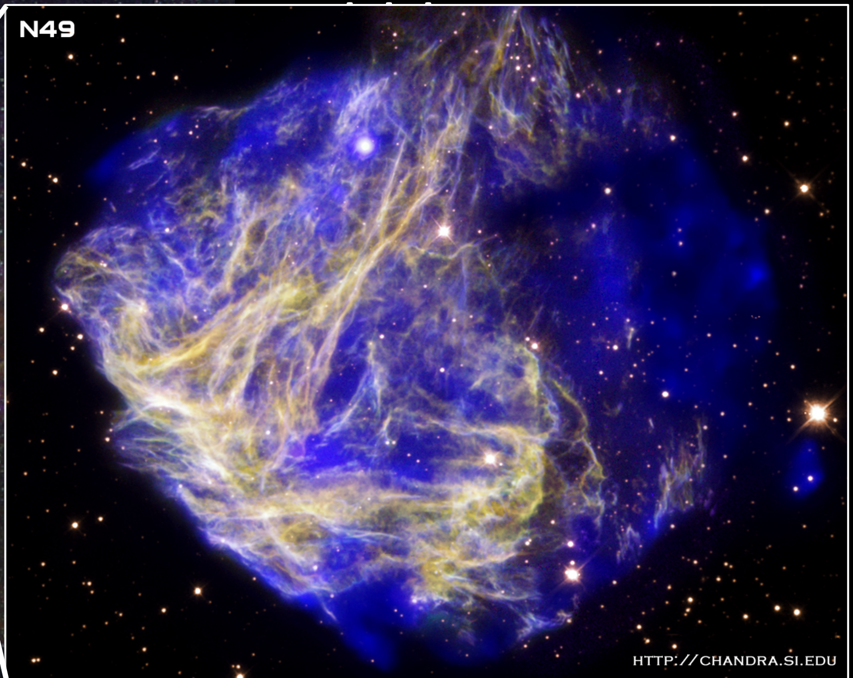
Bubbles, SNRs
~ 10 - 50 pc
~ 10^3 – 10^5 yr
(single star)

Superbubbles
~ 100 pc
~ 10^6 yr
(multiple stars)

Supergiant shells
~ 1000 pc
~ 10^7 yr
(multi generations)

R - Hα
G - [S II]
B - [O III]





(multiple stars)

Supergiant shells

~ 1000 pc

~ 10^7 yr

(multi generations)

R - Hα

G - [S II]

B - [O III]

Signatures of Classical SNRs

- **Bright X-ray emission**

  $L_x > 10^{35}$ ergs/s

- **Nonthermal radio emission**

  $S_\nu \propto \nu^{-\alpha}$ $\alpha \sim 0.5 - 0.8$

- **Enhanced [S II] emission**

  [S II]/Hα > 0.45

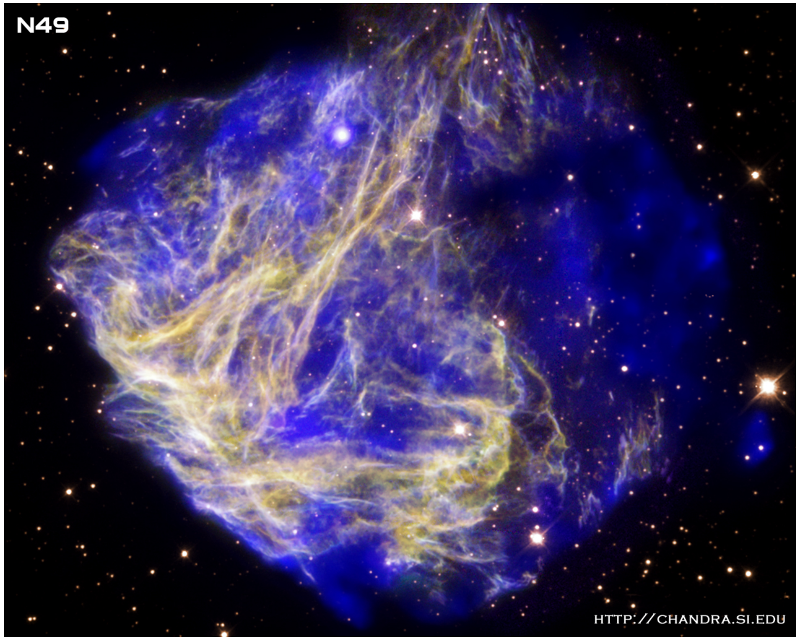
- **High-velocity gas (Hα line)**

  ionized gas $\Delta V > 100$ km/s

Example SNRs in the LMC

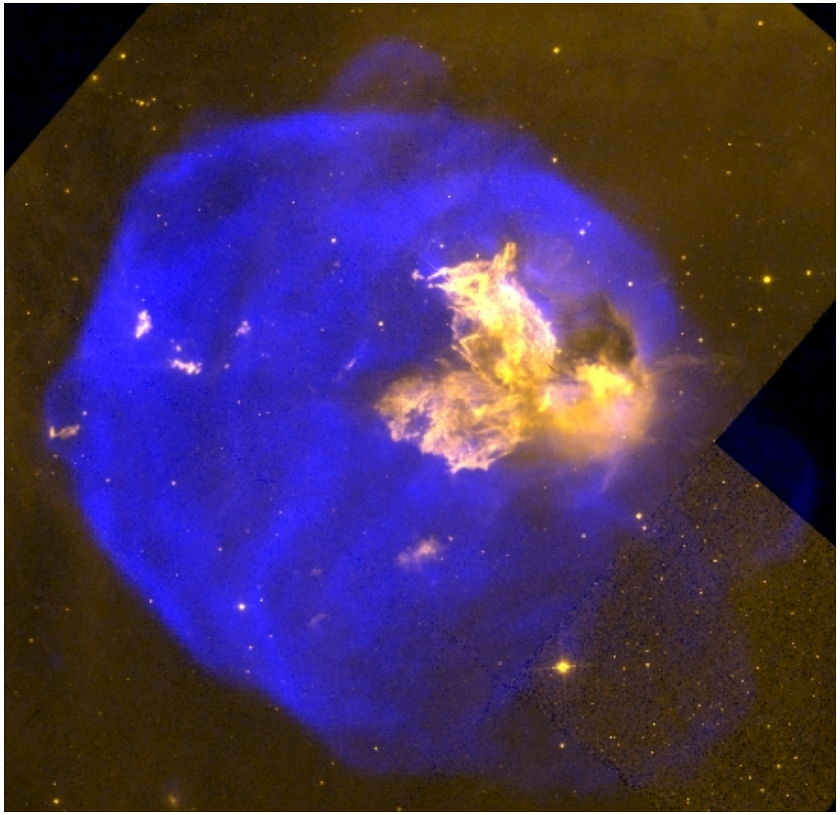
Size ~ 20pc

N49 (B-star progenitor)



Blue: X-ray
Other: optical/IR

N63A (O-star progenitor)



Identification of Type Ia SNRs

- **Balmer-dominated**

  SN ejecta running into a neutral medium; collisionless shock (Chevalier et al. 1980)

Size ~ 7 pc

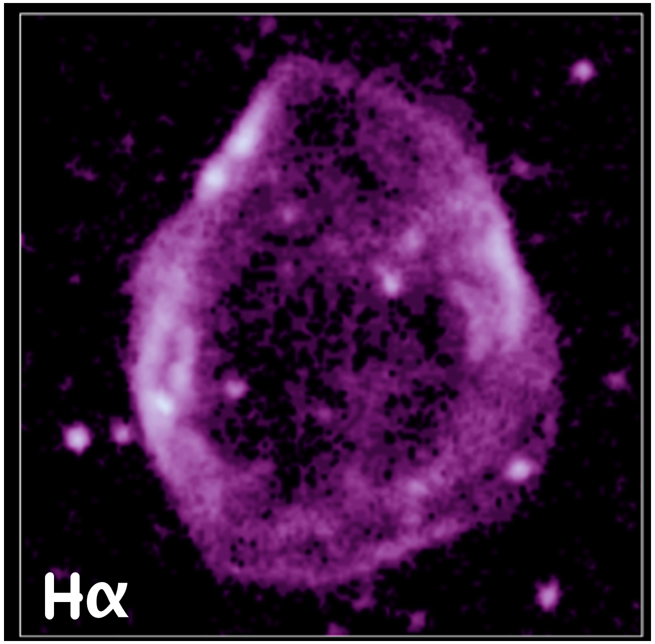
SNR 0509-67.5

Hα + X-ray

Identification of Type Ia SNRs

- Balmer-dominated
- X-ray Kα emission of Si,S,Ar,Ca,Fe

DEM L71 Size ~ 20 pc



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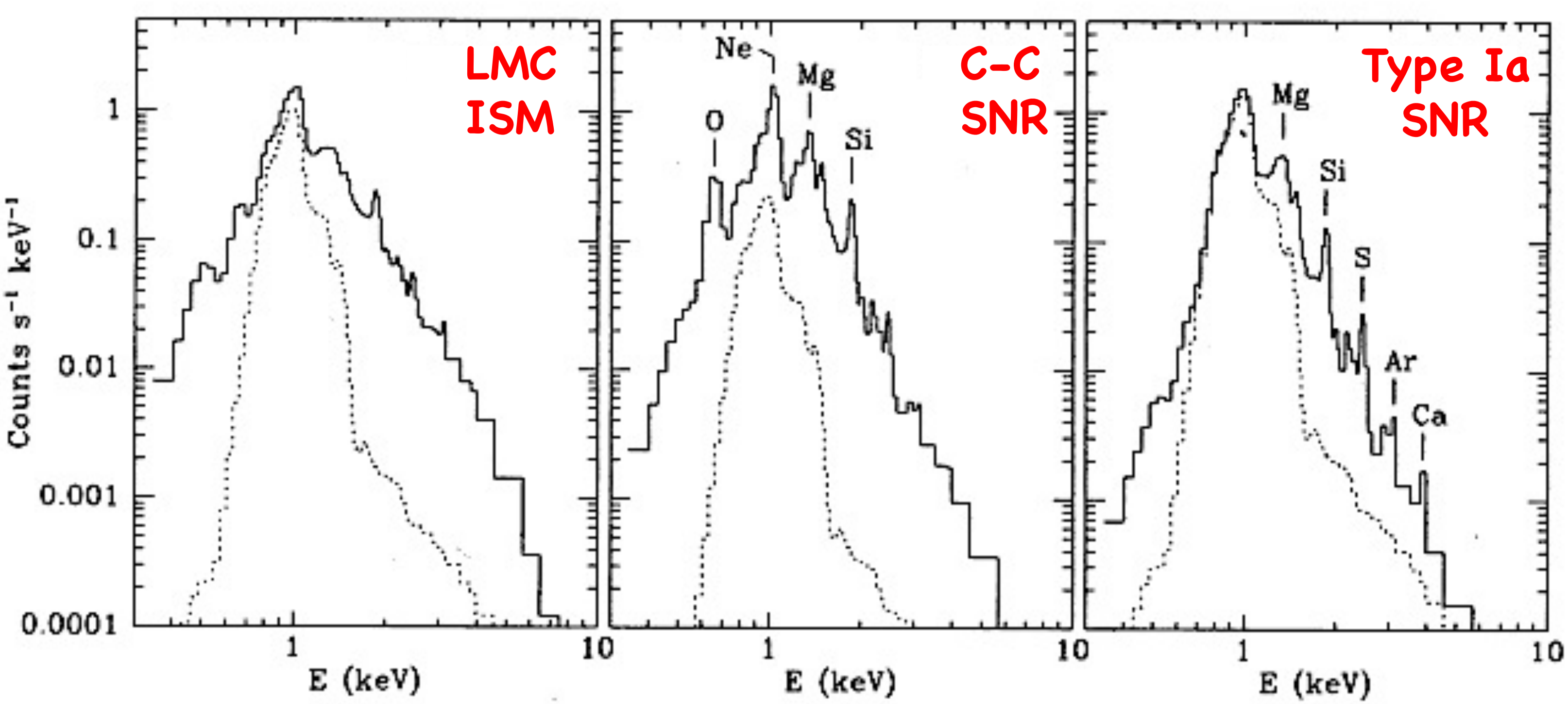
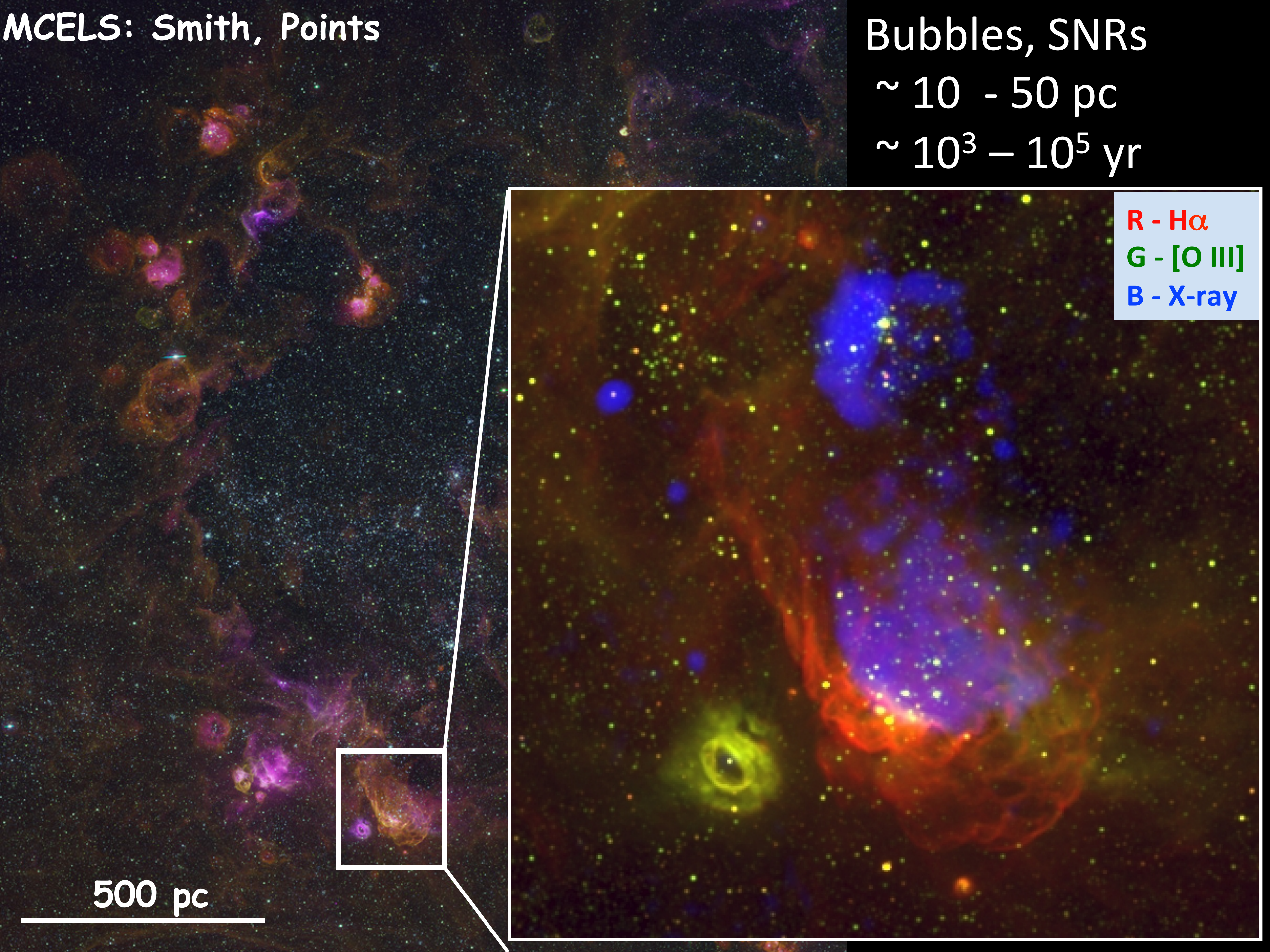


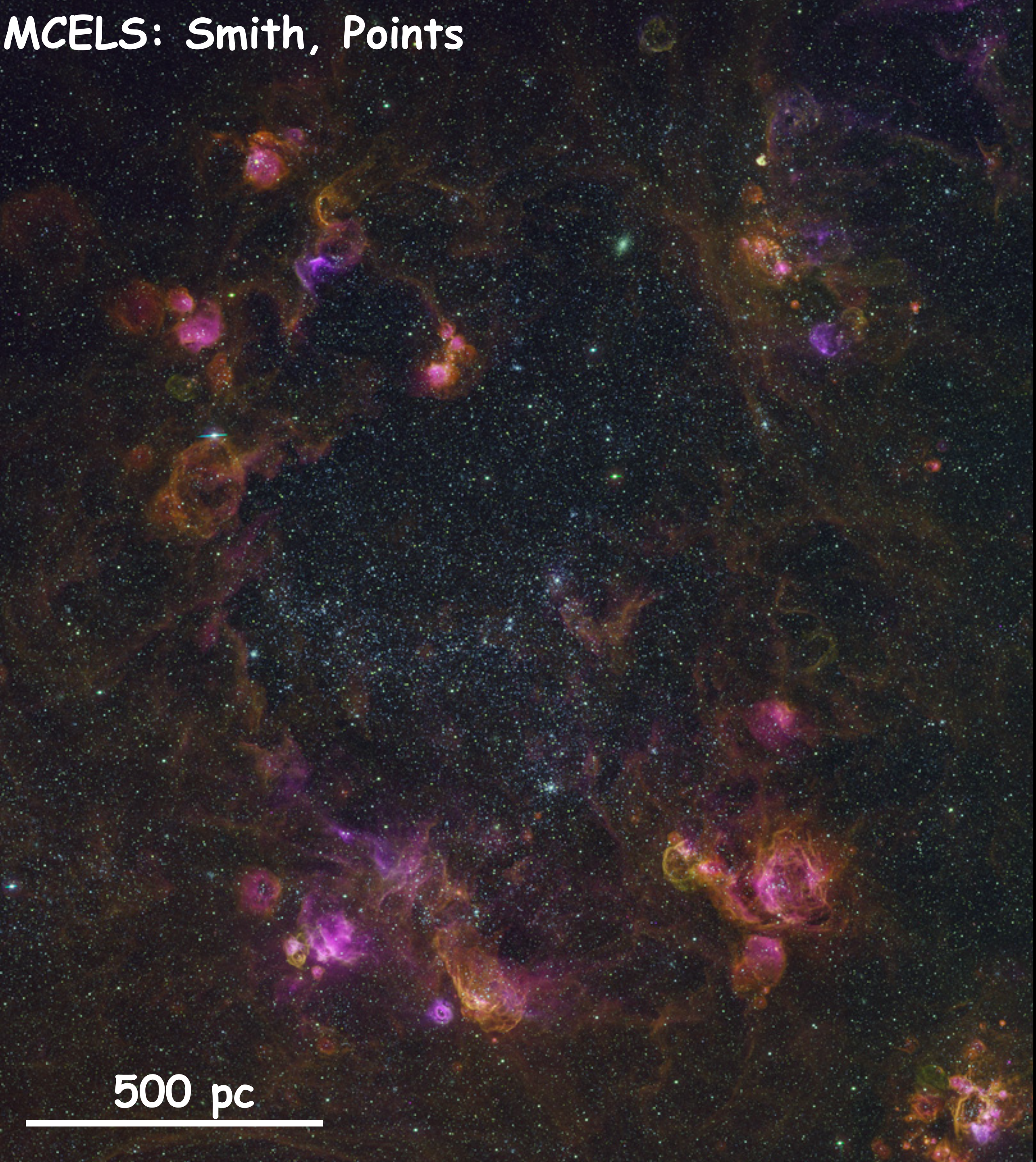
Hughes et al. 1995

Bubbles, SNRs

~ 10 - 50 pc

~ $10^3 - 10^5$ yr





Bubbles, SNRs

~ 10 - 50 pc

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(single star)

Superbubbles

~ 100 pc

~ 10^6 yr

(multiple stars)

Supergiant shells

~ 1000 pc

~ 10^7 yr

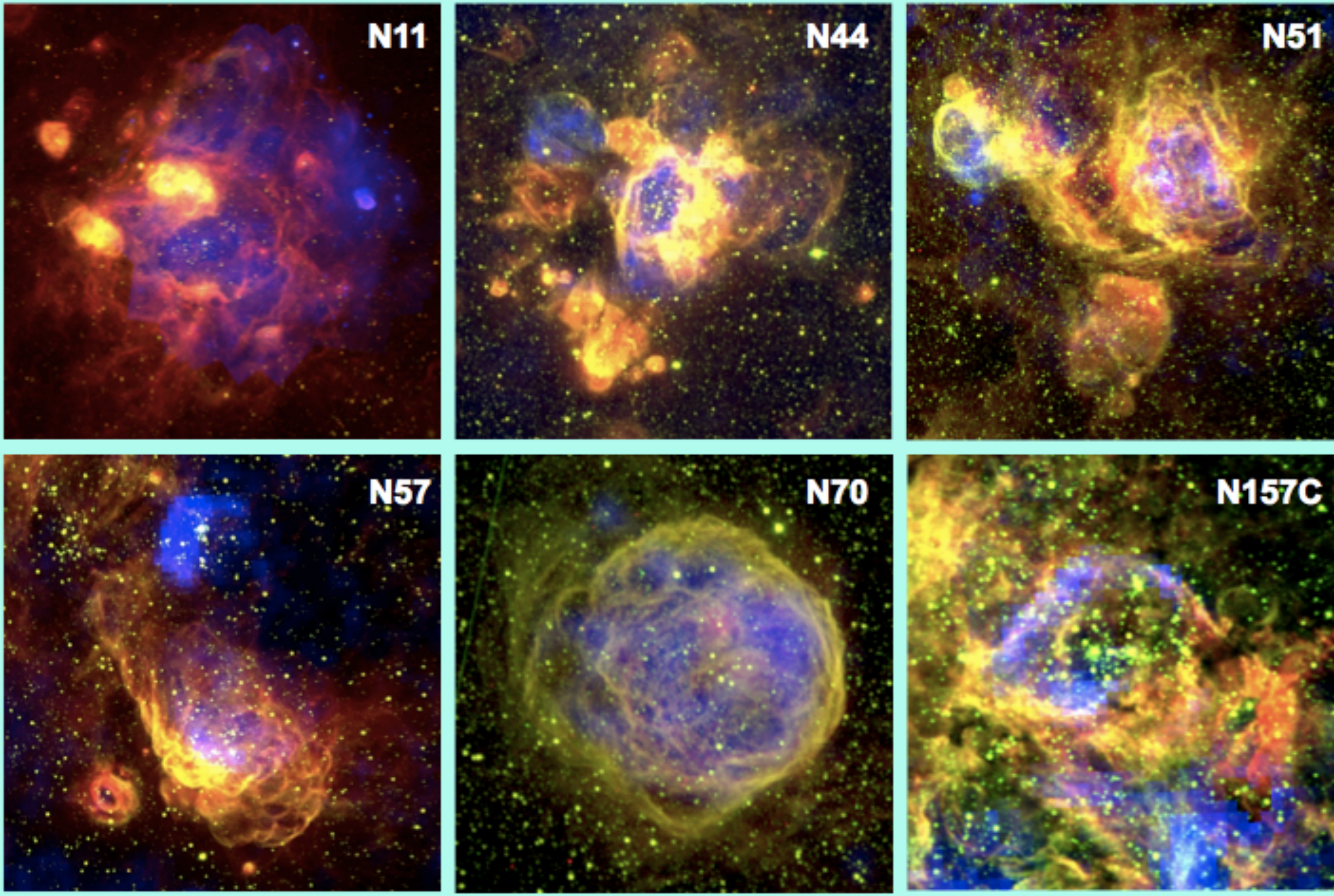
(multi generations)

R - Hα

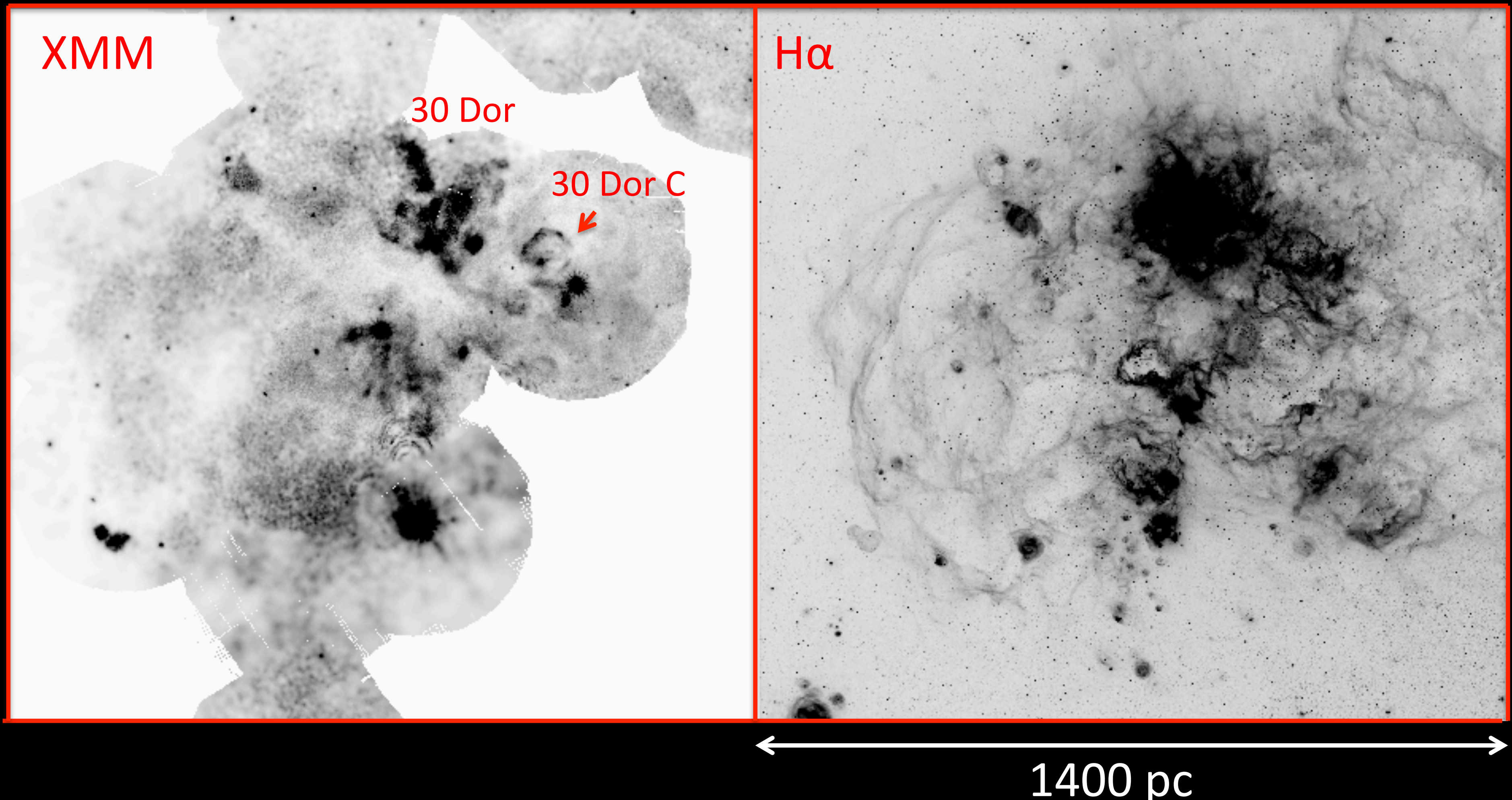
G - [S II]

B - [O III]

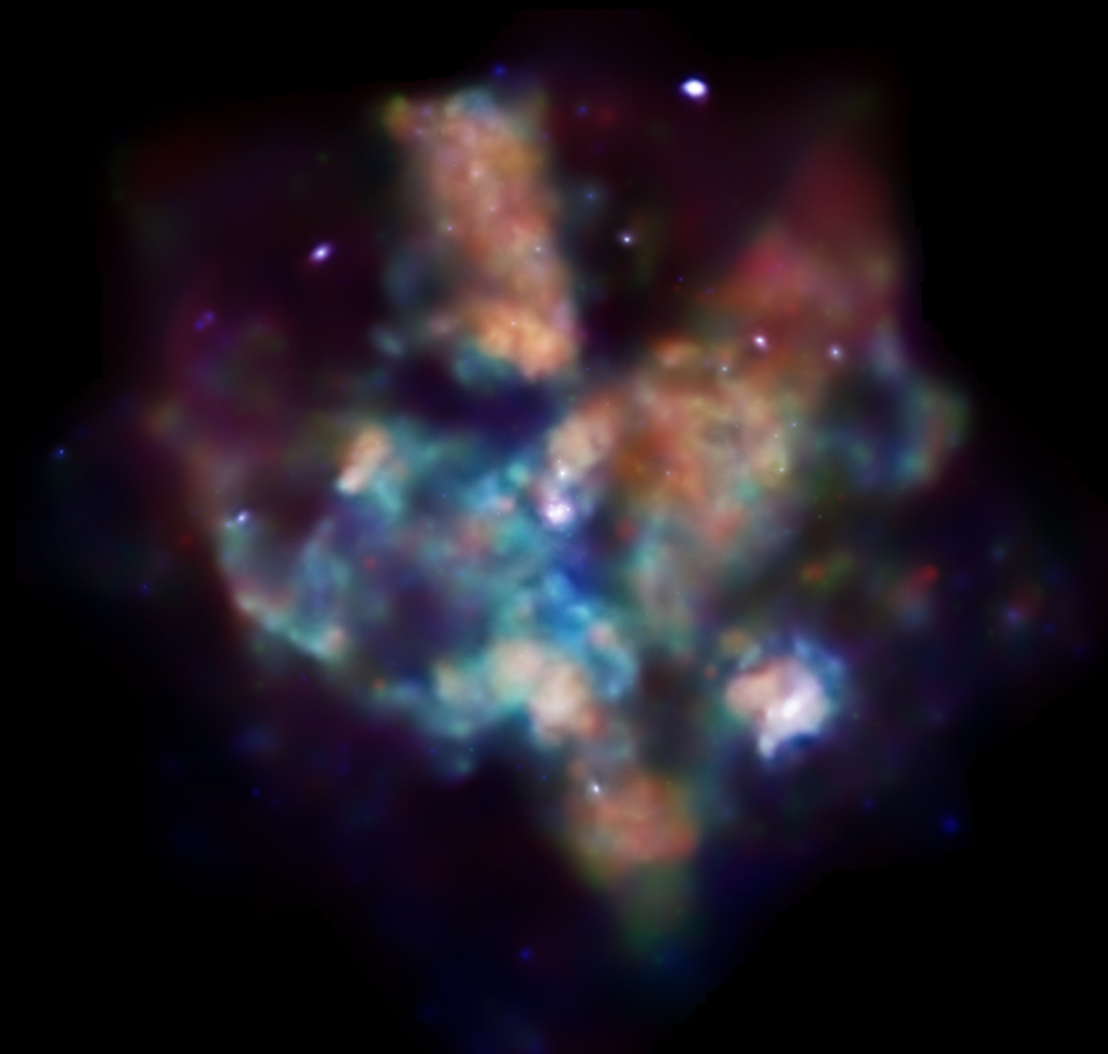
X-ray-bright Superbubbles



Hot Gas in Interstellar Structures

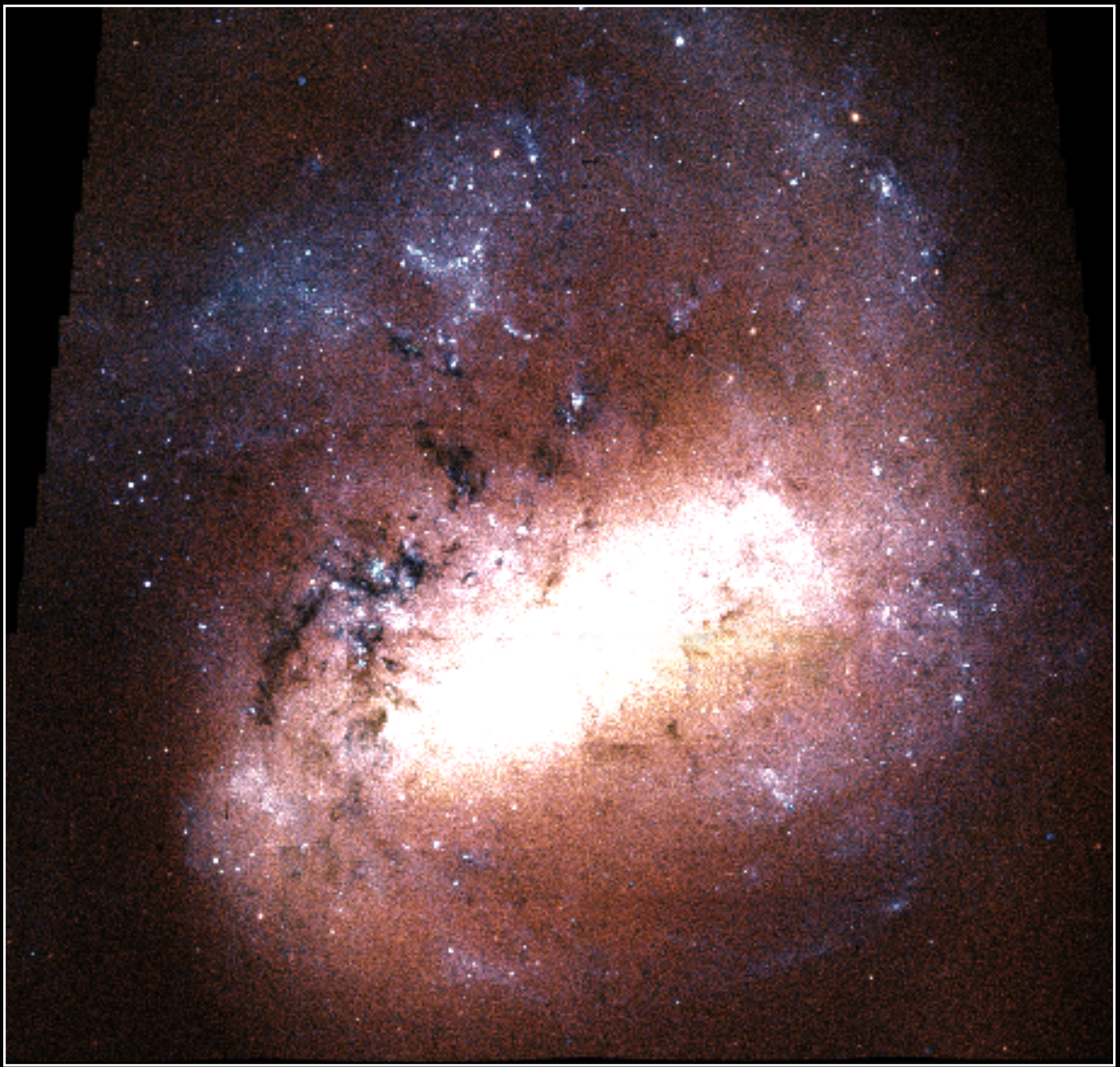


Chandra X-ray Image of Hot Gas in 30 Dor



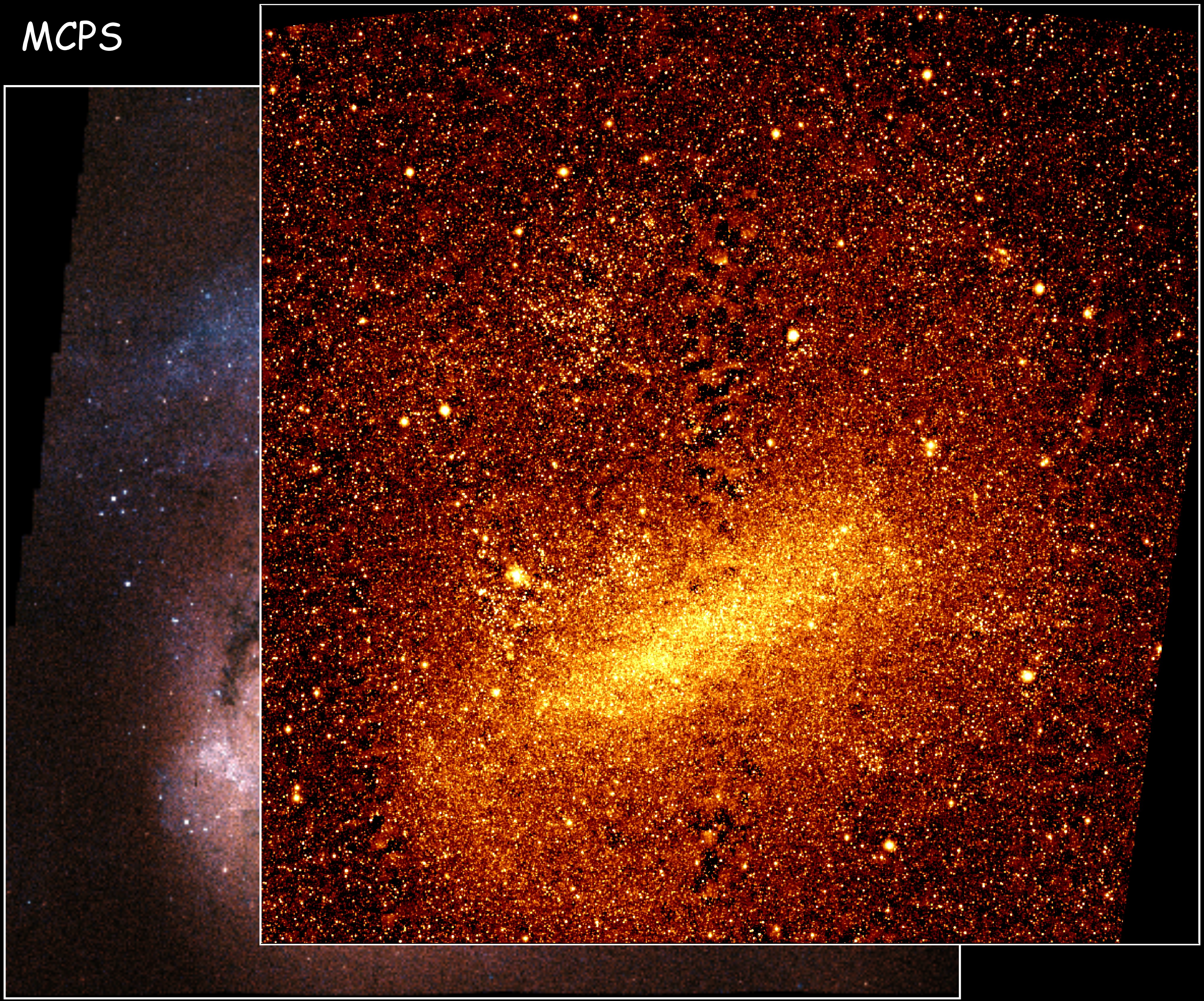
Townsley et al. (2006)

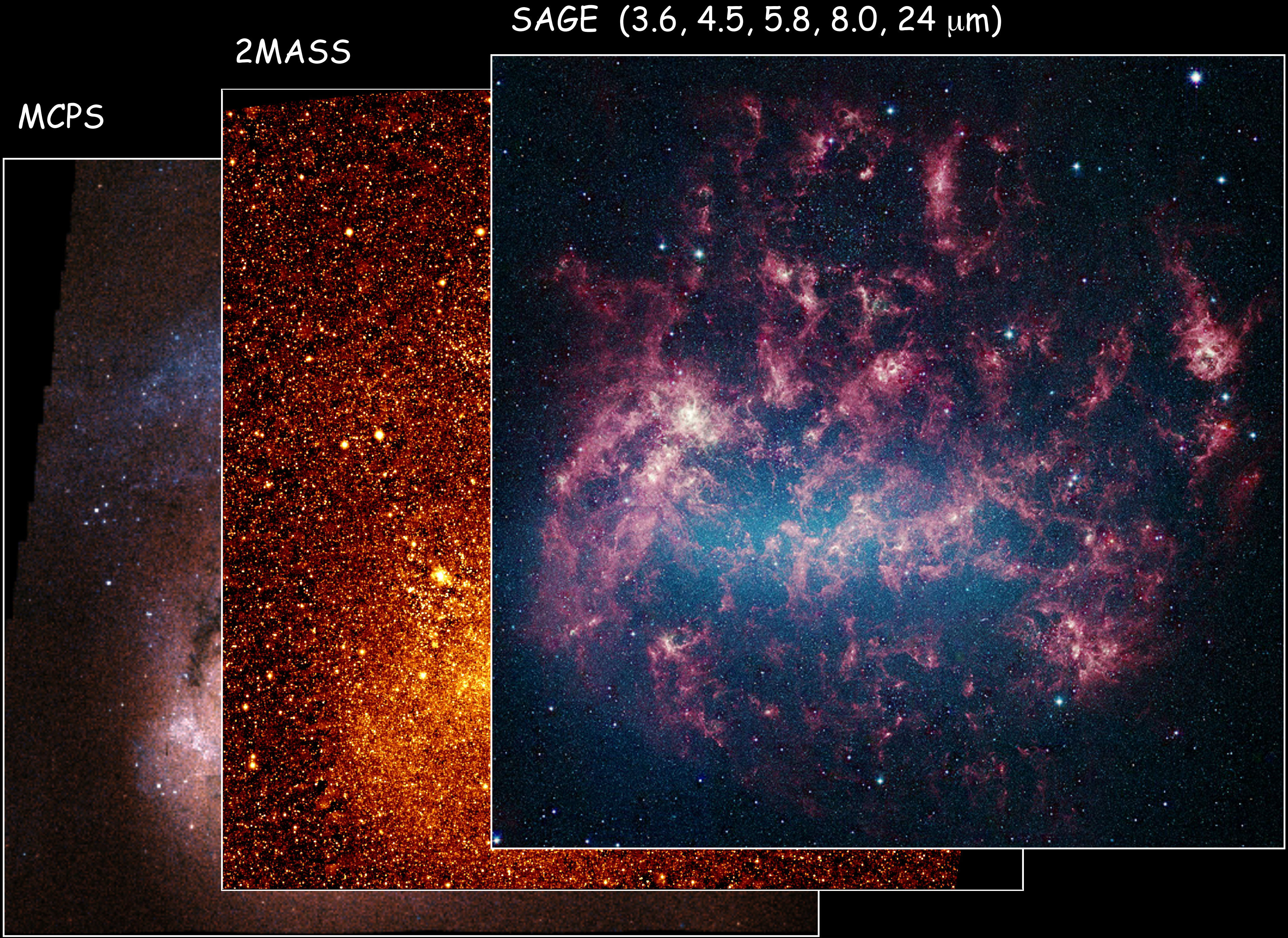
MCPS (UBVI)



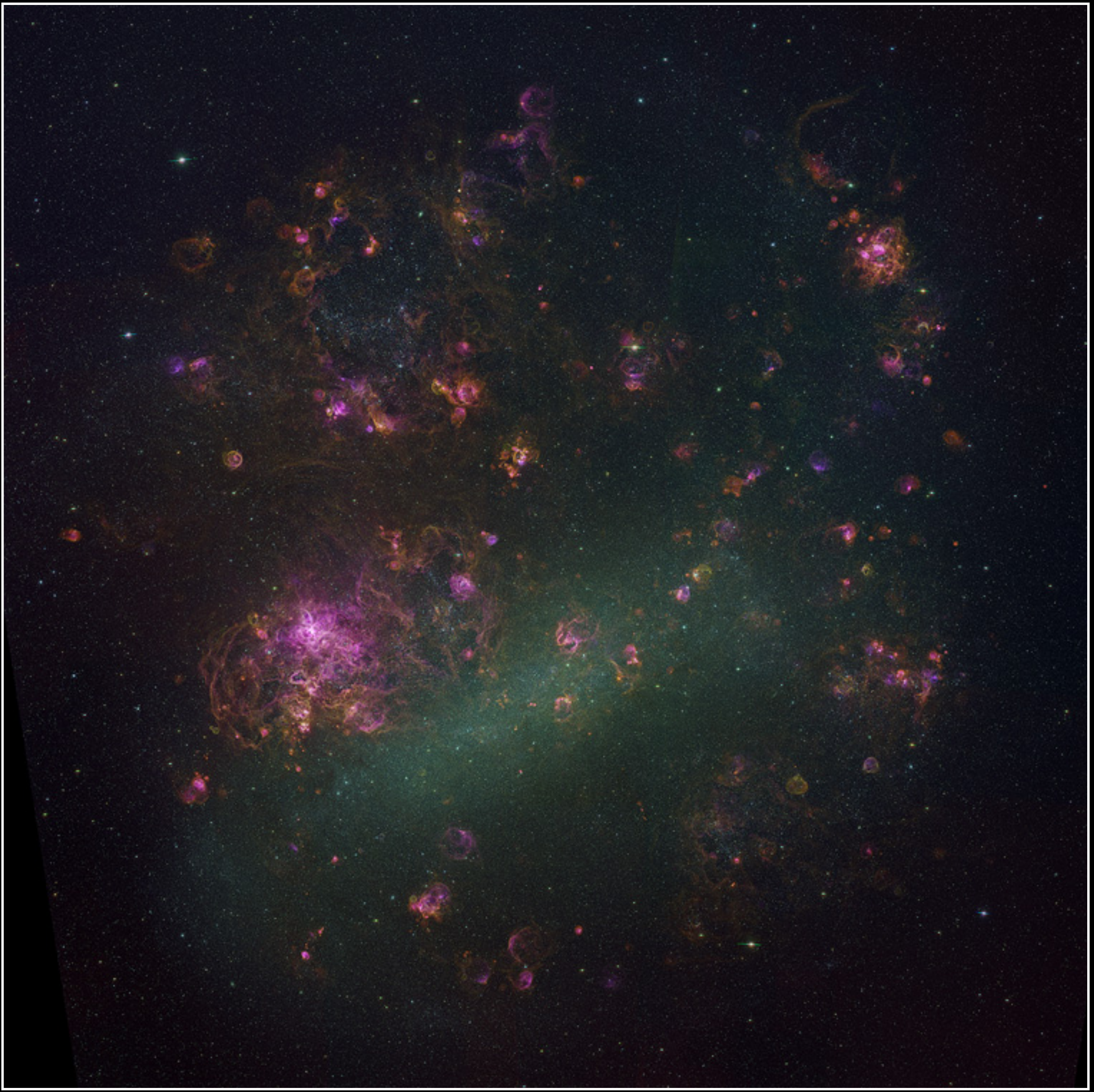
2MASS (JHK)

MCPS



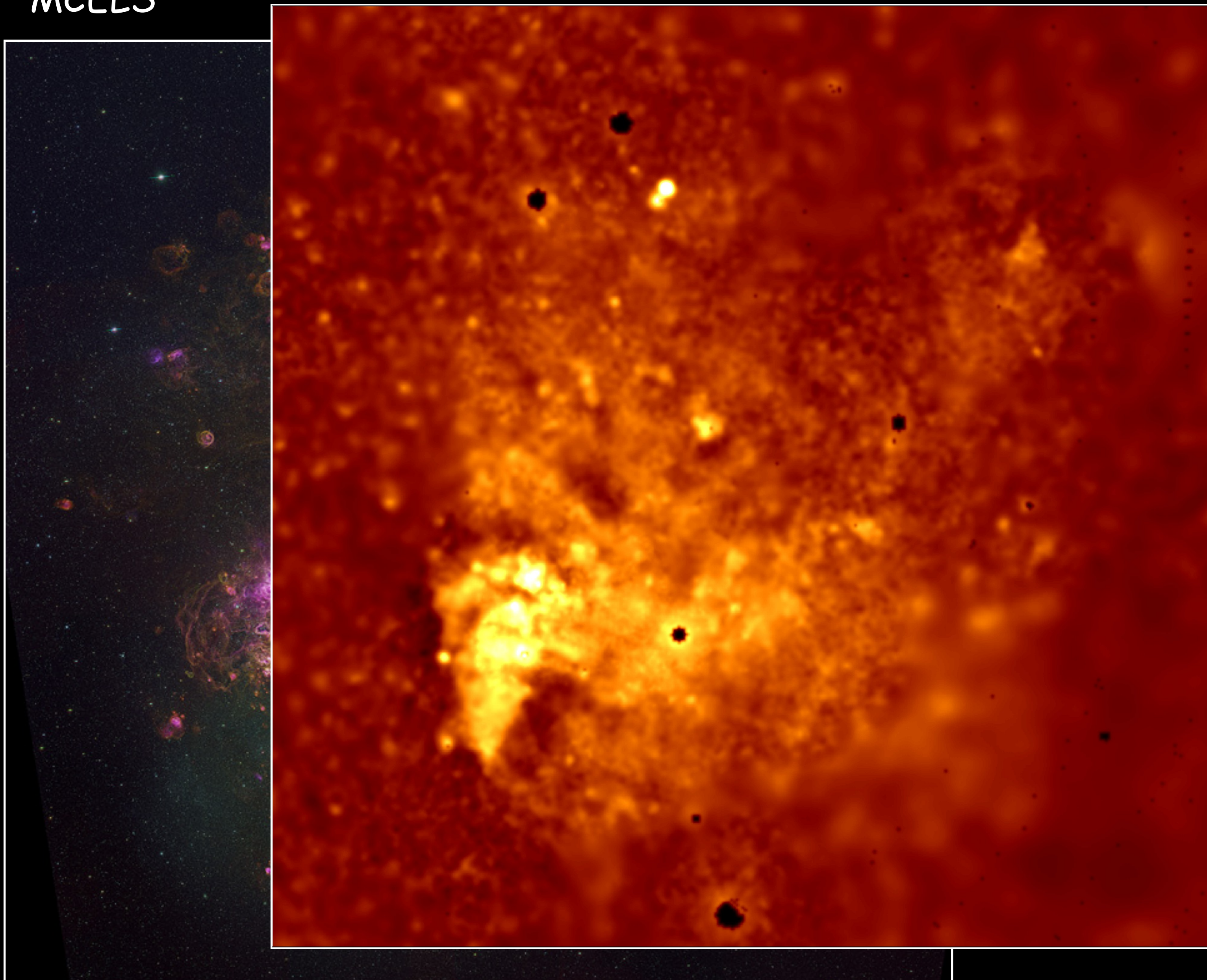

SAGE (3.6, 4.5, 5.8, 8.0, 24 μm)
2MASS
MCPS

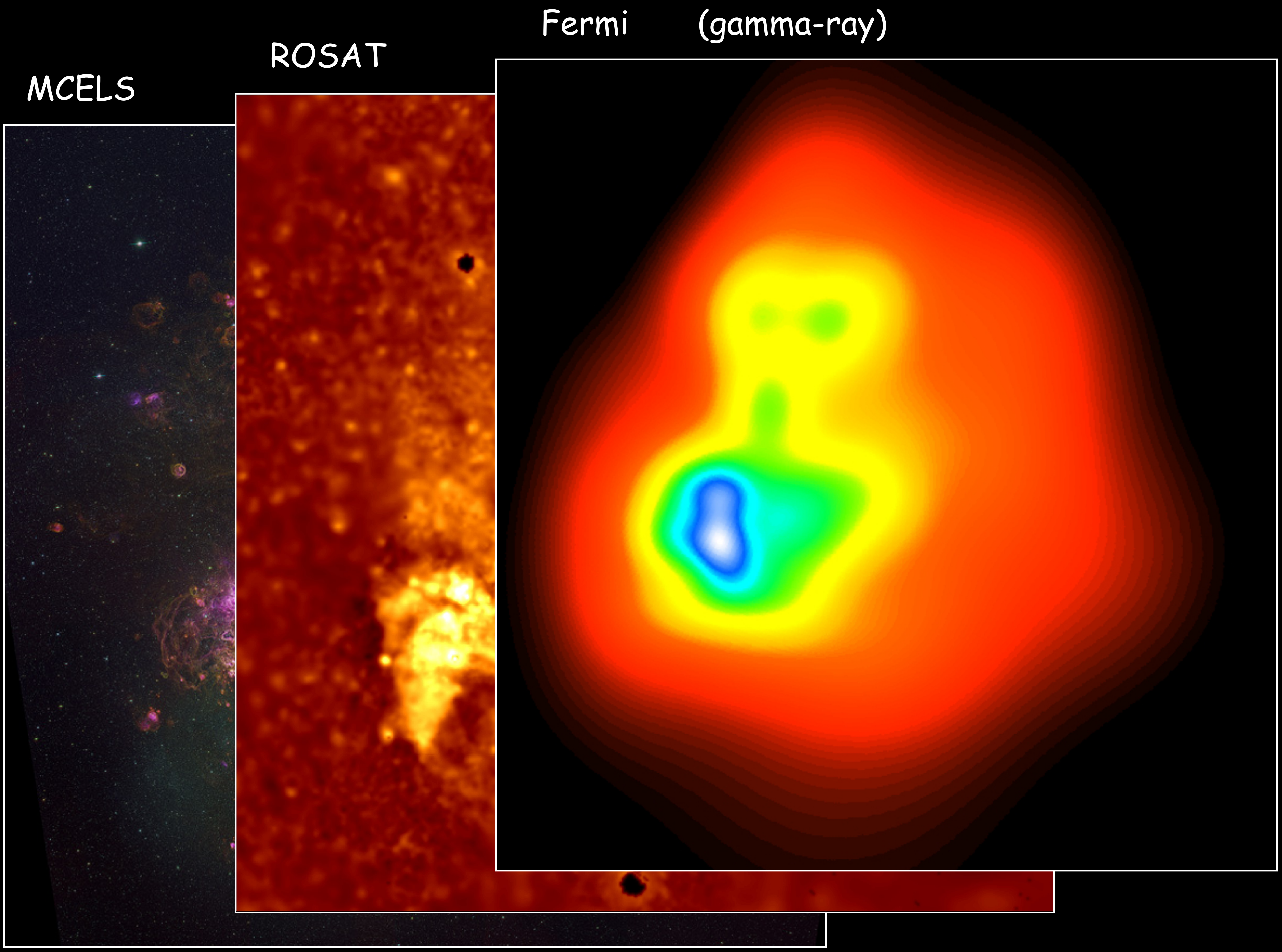
MCELS (Hα, [O III], [S II])



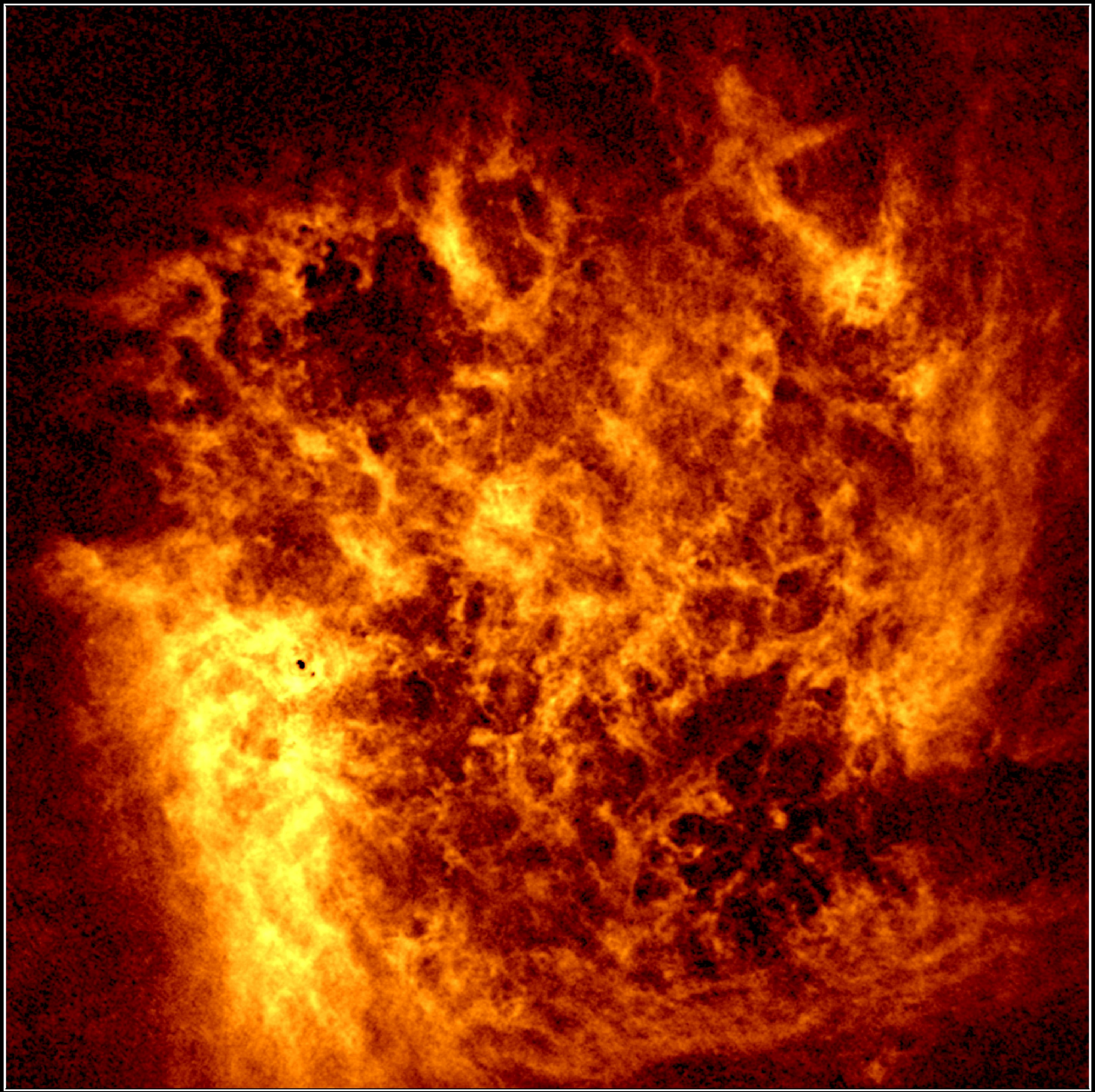
ROSAT (X-ray, 0.1-2.4 keV)

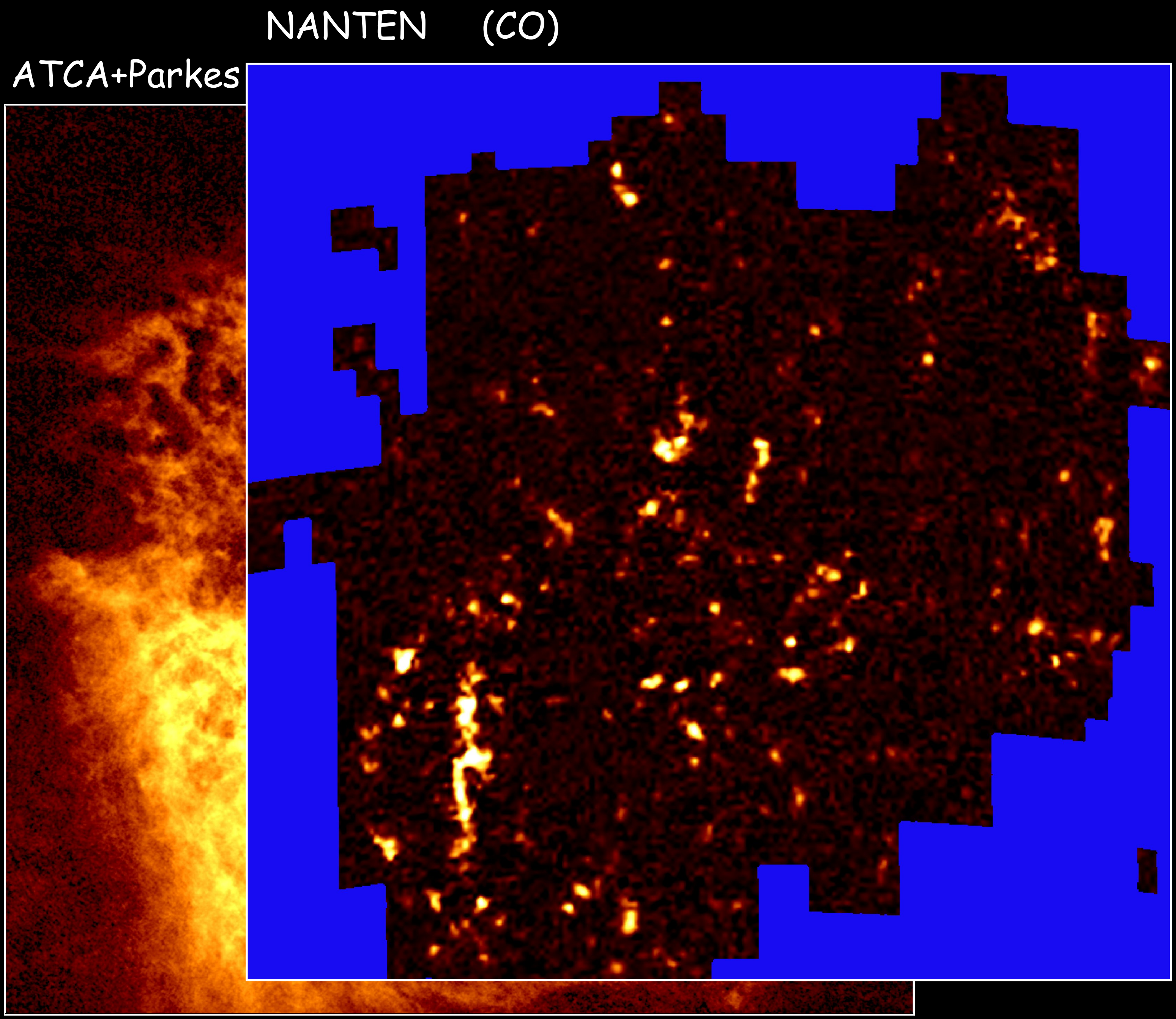
MCELS




MCELS
ROSAT
Fermi (gamma-ray)

ATCA+Parkes (H I)




NANTEN (CO)
ATCA+Parkes