

Systematic Study of HII regions in the Magellanic Clouds with eROSITA

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eRO-STEP
FOR2990



Deutsche
Forschungsgemeinschaft

HII regions – What? Where? Why?

❑ What?

Region of ionized gas surrounding one or multiple MASSIVE STARS, generated by their radiation and winds.

❑ Where?

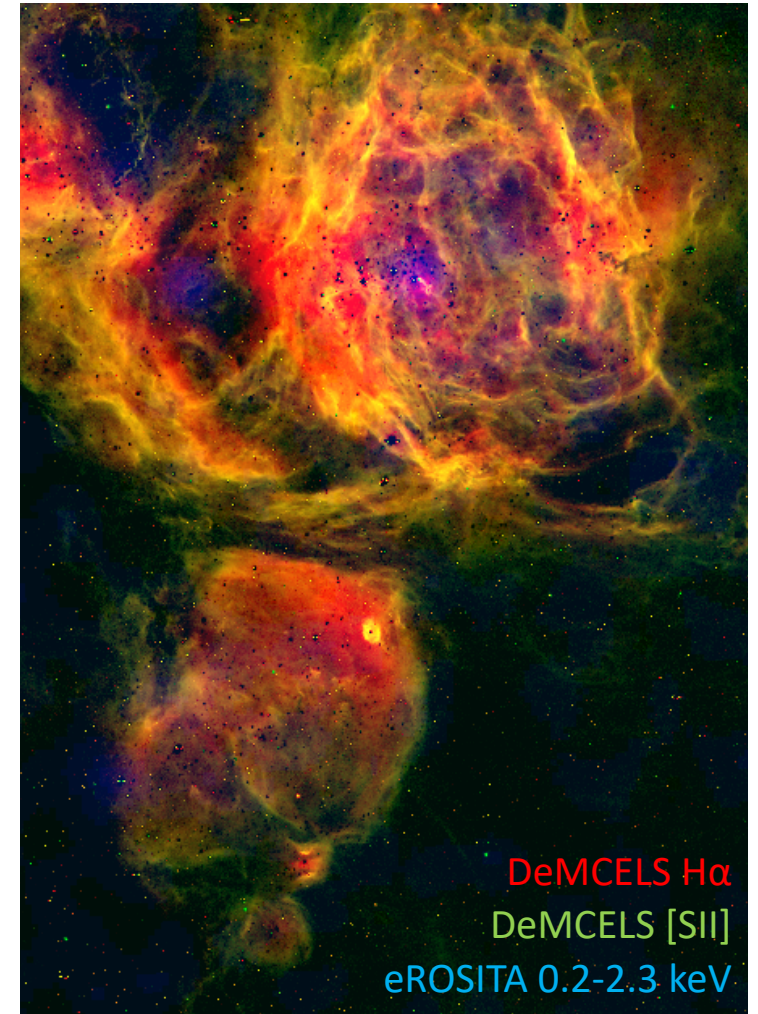
In star-forming regions

❑ Why?

HII regions and SNR shape the ISM and are key to understand the baryonic cycle.

Regions of stellar birth and stellar death

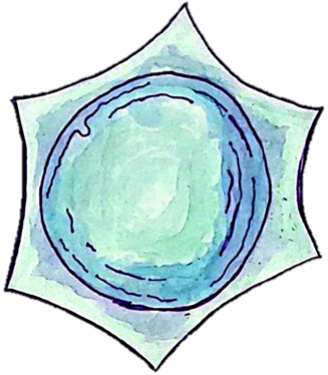
Interaction between the different phases of the ISM



N51D and N51E, two HII regions from the LMC

HII regions - Standard Bubble Model

Massive star

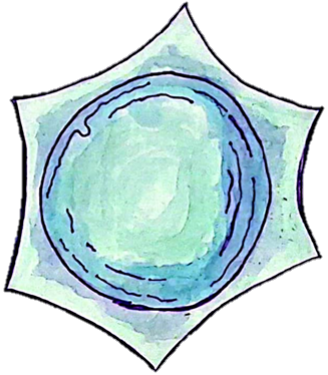


Weaver R. + (1977)

HII regions - Standard Bubble Model

Radiation $\rightarrow$ Ionize medium: Optical lines ($T \sim 10^4 K$)

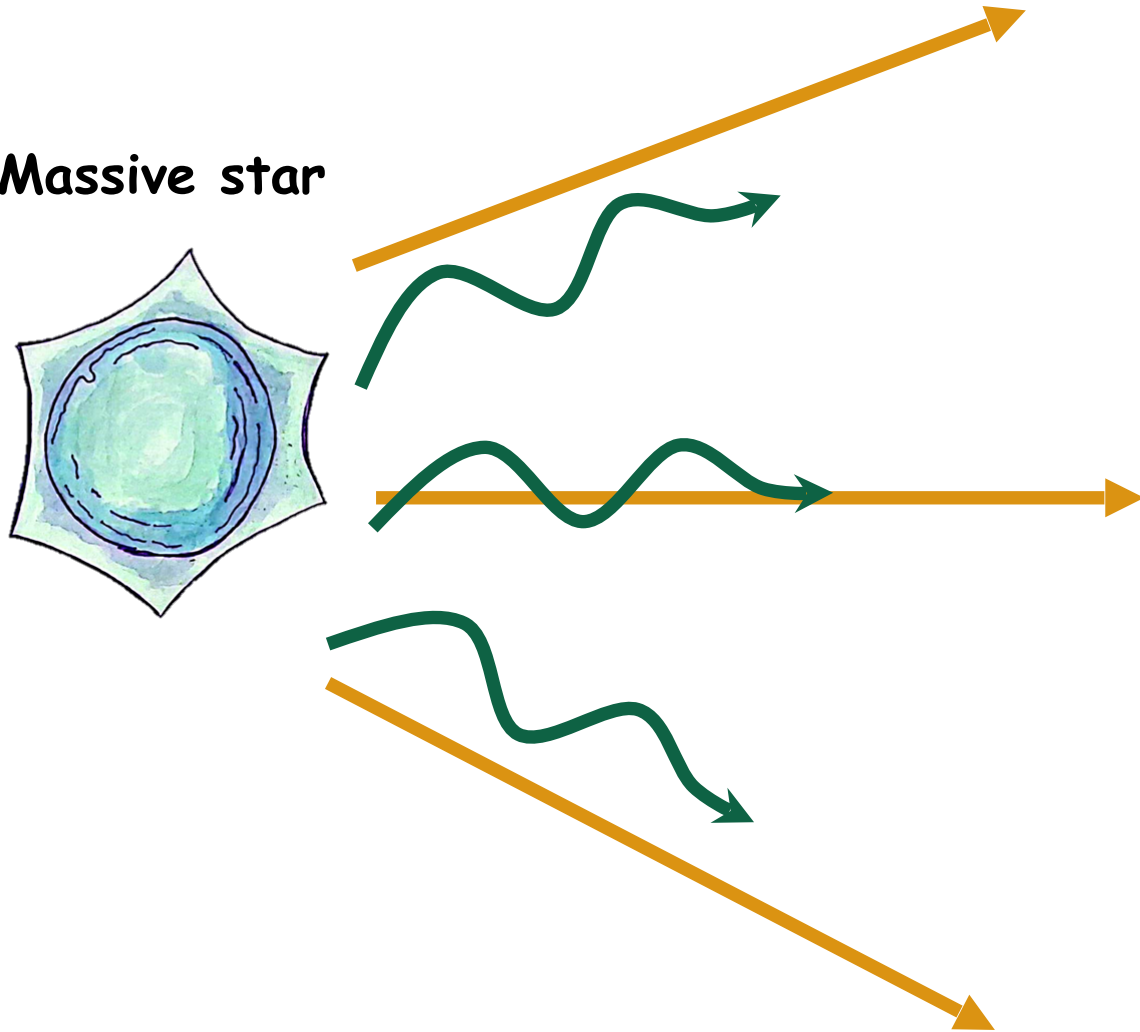
Massive star



Weaver R. + (1977)

HII regions - Standard Bubble Model

Massive star

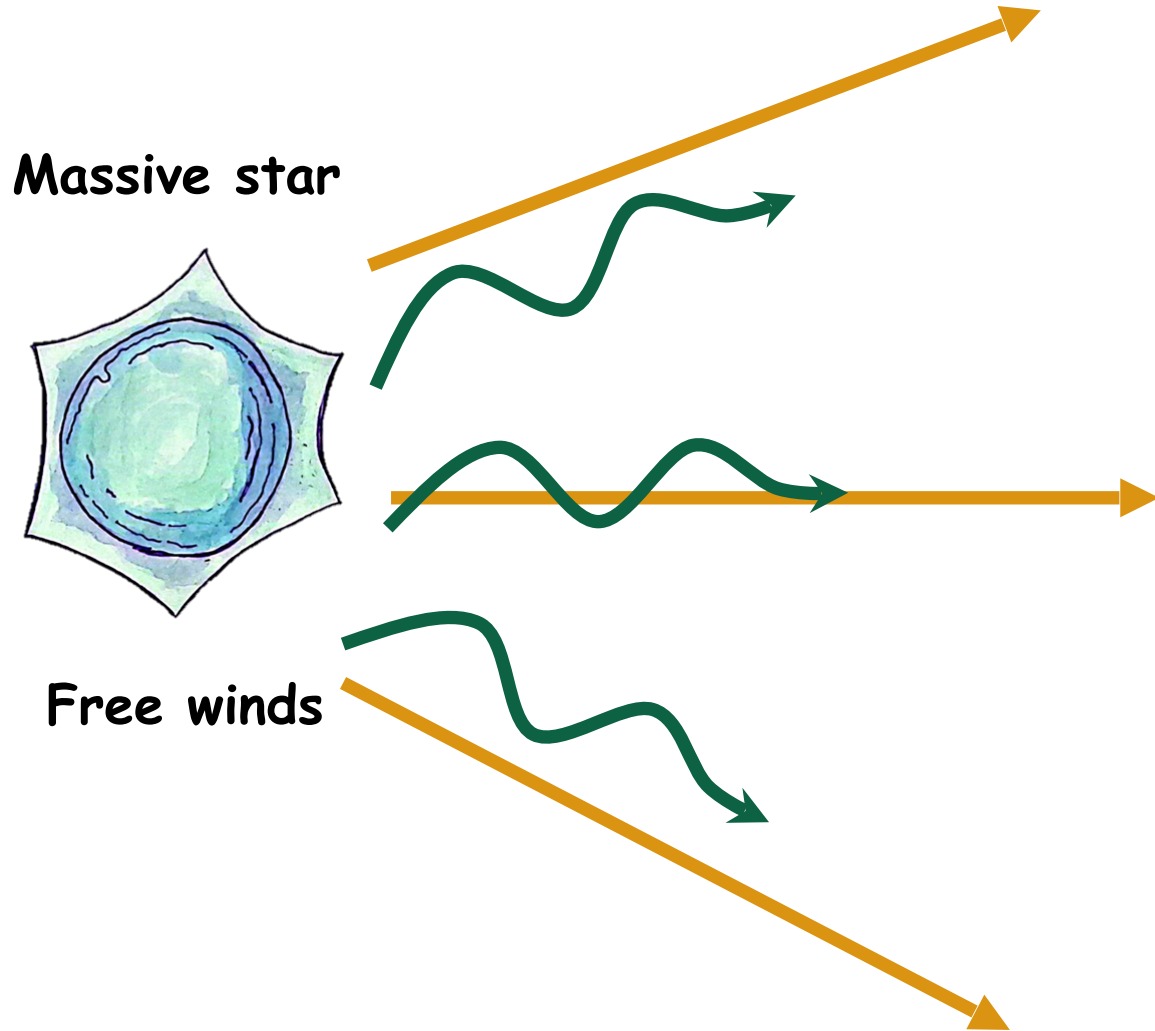


Radiation -> Ionize medium: Optical lines ($T \sim 10^4 K$)

Stellar Winds -> Shock the medium: Plasma ($T \sim 10^6 K$)

Weaver R. + (1977)

HII regions - Standard Bubble Model

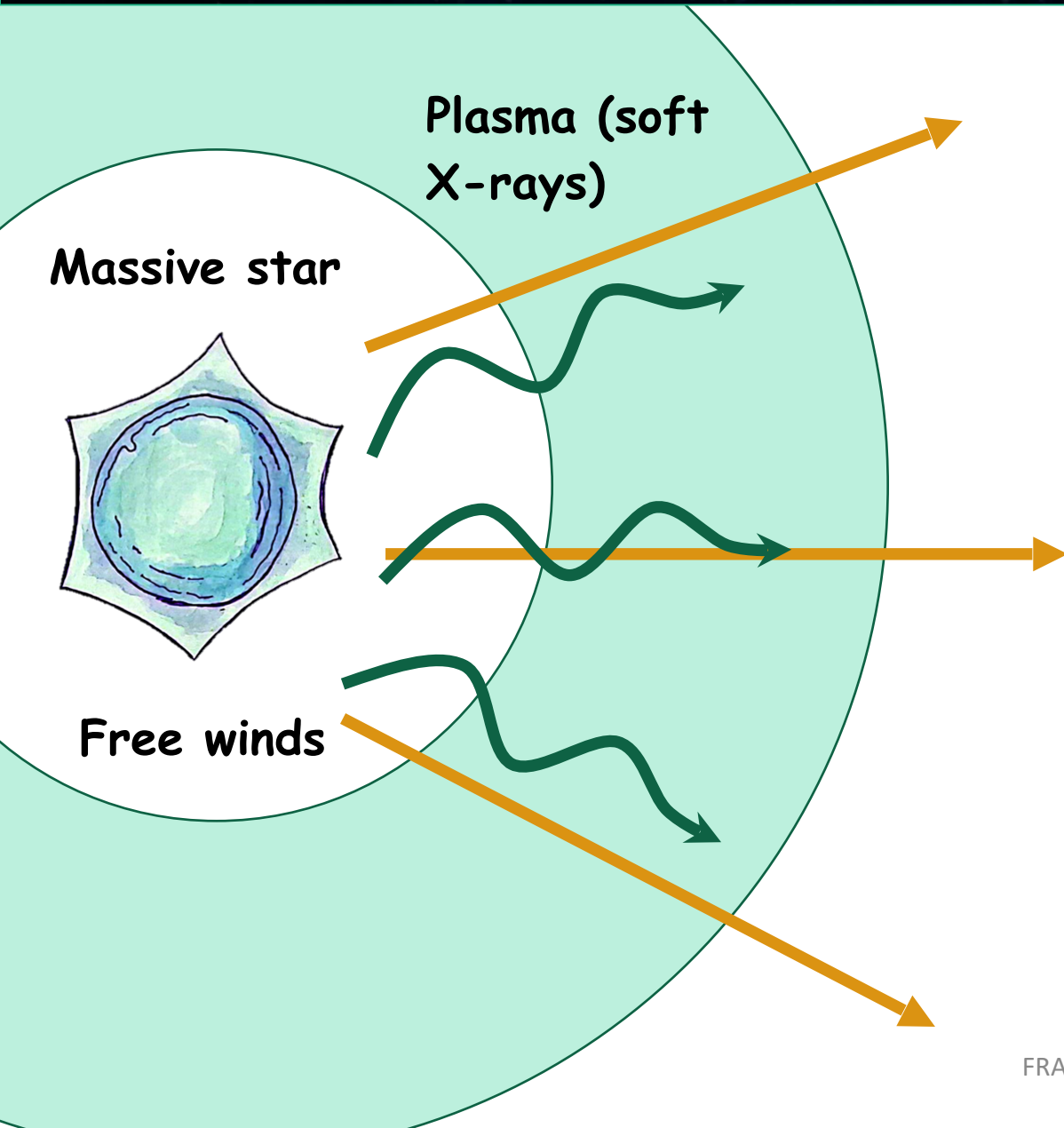


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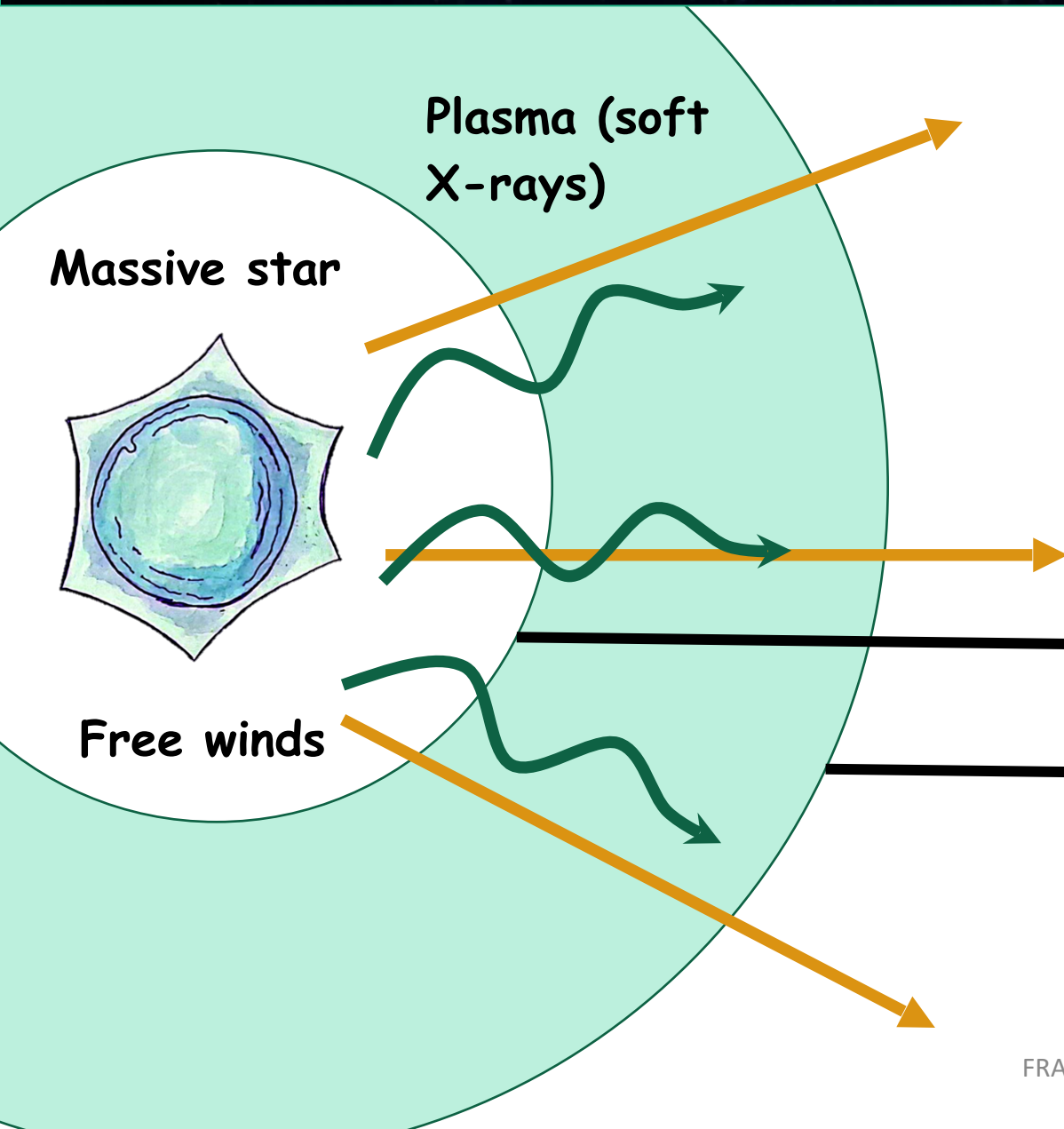


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HII regions - Standard Bubble Model



Radiation -> Ionize medium: Optical lines ($T \sim 10^4 K$)

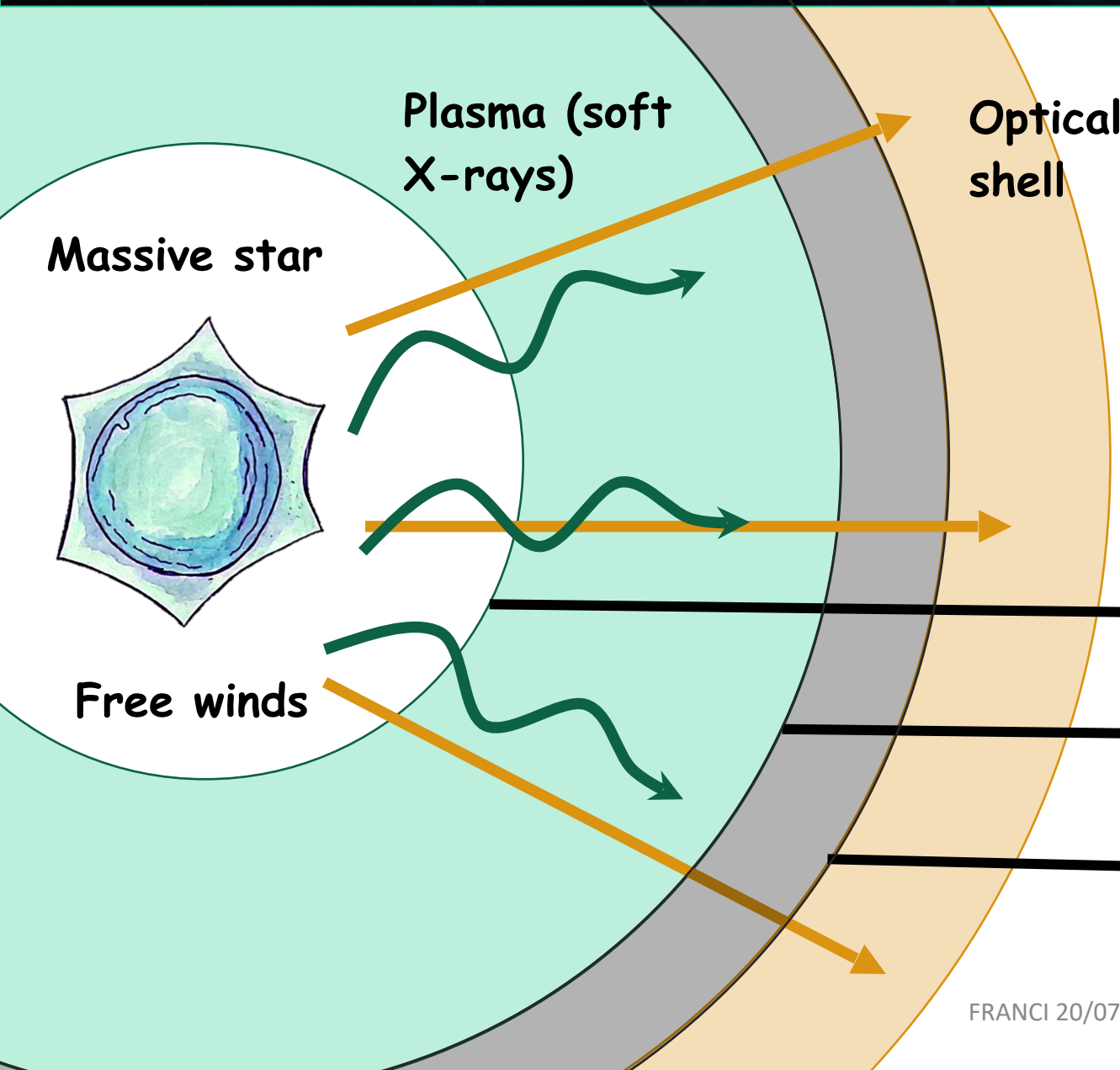
Stellar Winds -> Shock the medium: Plasma ($T \sim 10^6 K$)

Weaver R. + (1977)

Reverse shock

Contact discontinuity

HII regions - Standard Bubble Model



Radiation -> Ionize medium: Optical lines ($T \sim 10^4 K$)

Stellar Winds -> Shock the medium: Plasma ($T \sim 10^6 K$)

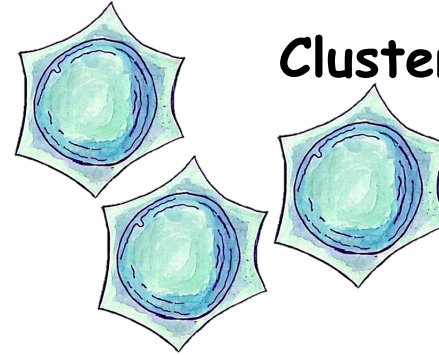
Weaver R. + (1977)

Reverse shock

Contact discontinuity

External shock

HII regions - Superbubbles (SB)

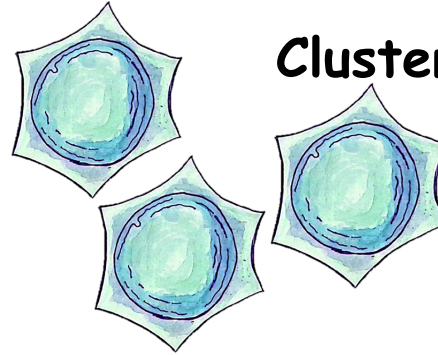


Cluster / OB Association

HII regions - Superbubbles (SB)



**Stellar
Winds**

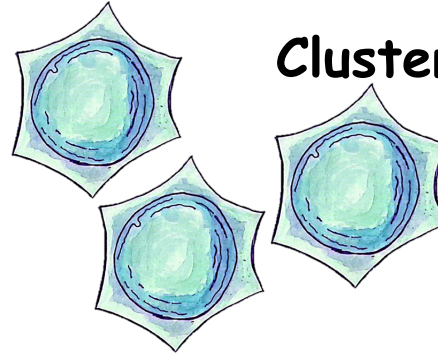


Cluster / OB Association

HII regions - Superbubbles (SB)



Stellar
Winds



Cluster / OB Association



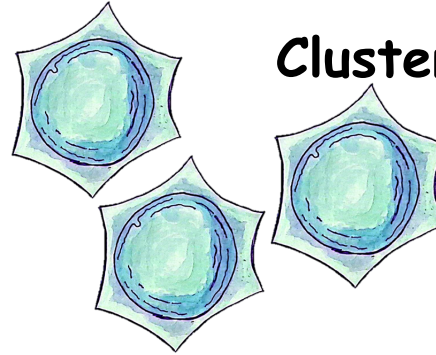
SNe

HII regions - Superbubbles (SB)

Time/Moment
of observation



Stellar
Winds



Cluster / OB Association



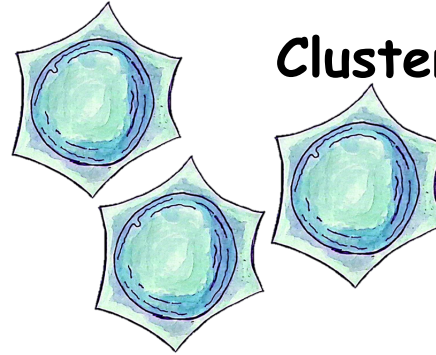
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HII regions - Superbubbles (SB)

Time/Moment
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Stellar
Winds



Cluster / OB Association



SNe

Dust, absorption
and environment

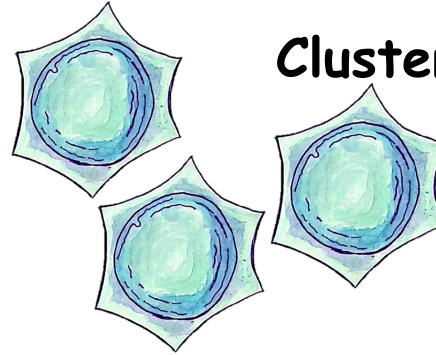


HII regions - Superbubbles (SB)

Time/Moment
of observation



Stellar
Winds



Cluster / OB Association

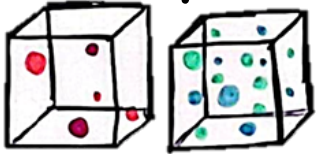


SNe

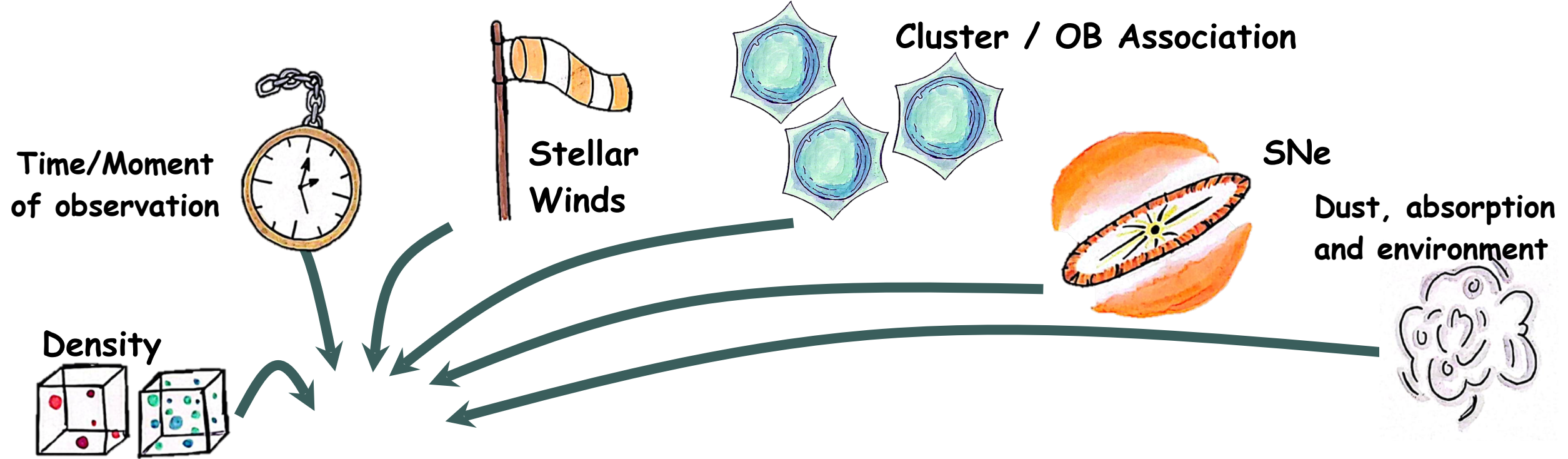
Dust, absorption
and environment



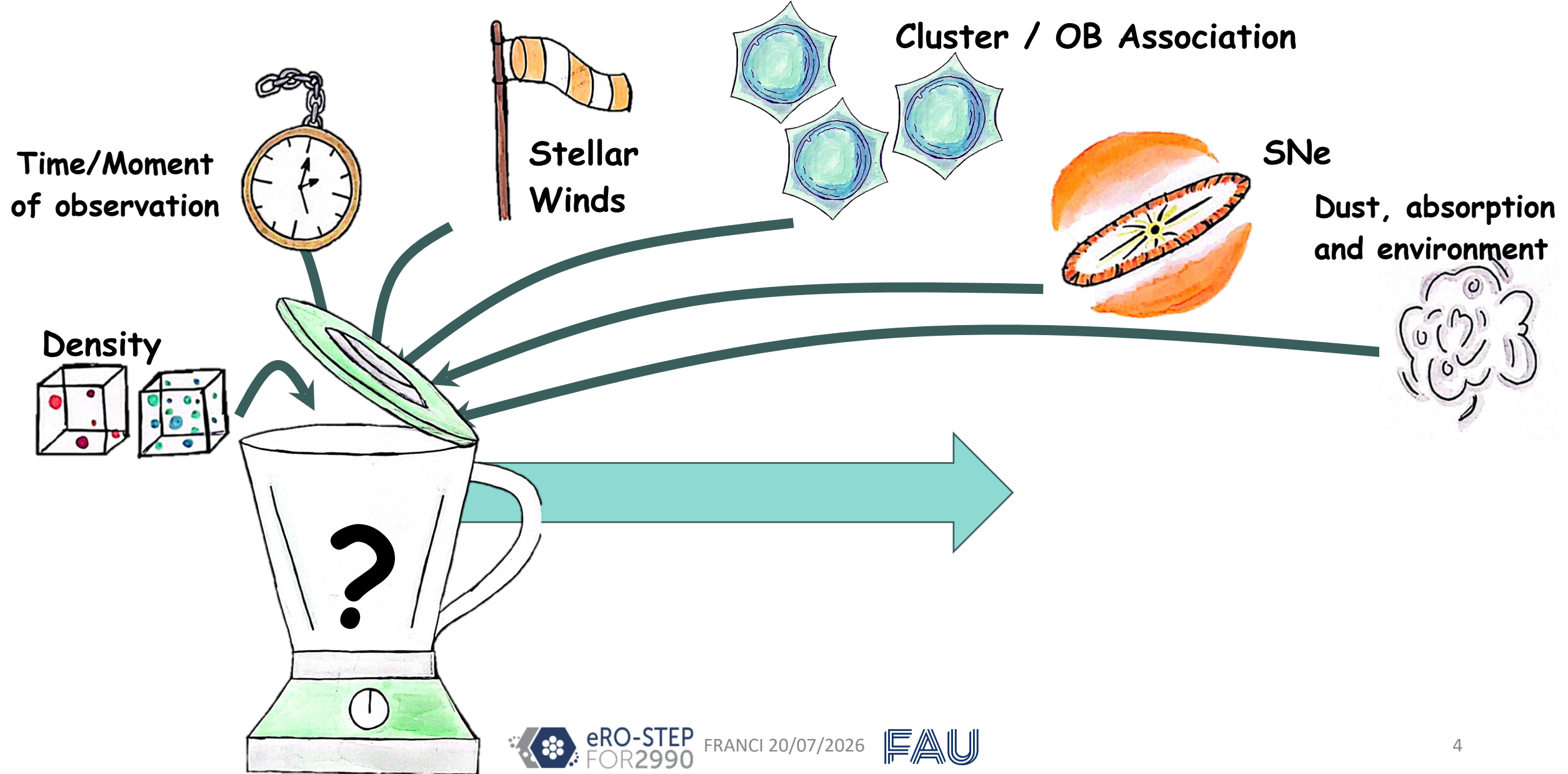
Density



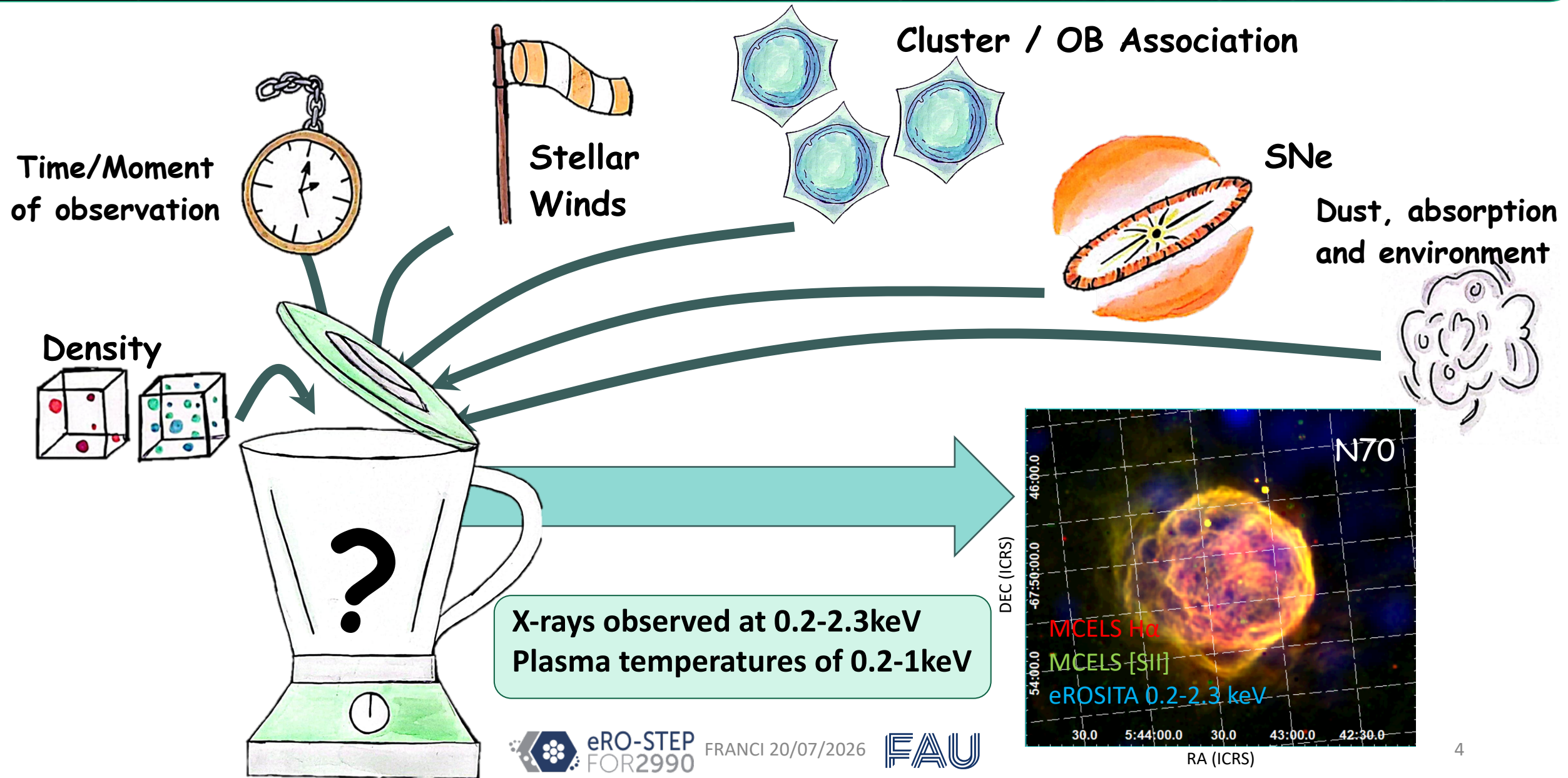
HII regions - Superbubbles (SB)



HII regions - Superbubbles (SB)



HII regions - Superbubbles (SB)



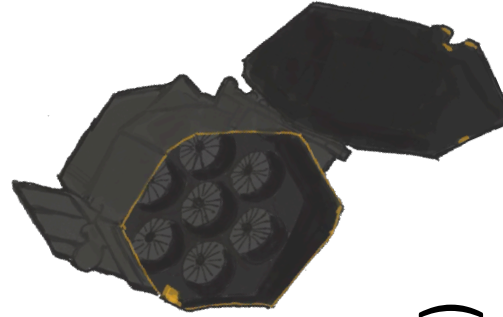
Large Magellanic Cloud

Ideal laboratory:

- Closest star forming galaxy to the MW: $\sim 50\text{kpc}$
- Low inclination ($i \sim 30\%$)
- Low absorption in the direction of LMC.
- Full or partial coverage by multiple missions.

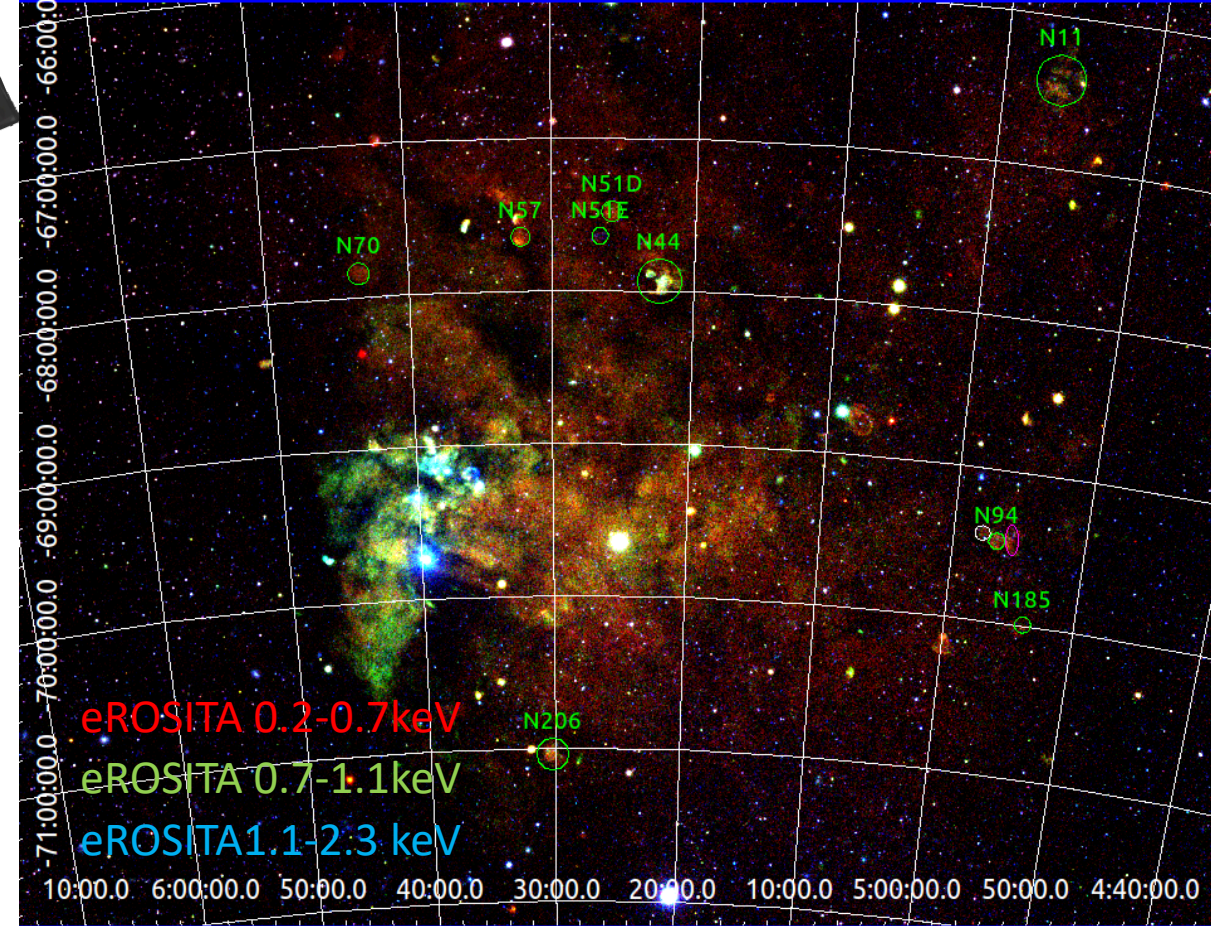
eROSITA

- Sharp and deep images over large sky areas (FOV $\sim 1^\circ$ diameter, avg resolution $\sim 26''$)
- Spectral information in the $\sim 0.2\text{-}10\text{ keV}$ range.



Credit: Aafia Zainab

DEC (ICRS)



RA (ICRS)

eROSITA view of the LMC. The green circles show the priority regions of study, and the well known N11, N44 and N206 regions.

Aims

Systematic study of HII regions in the MC (starting with LMC)

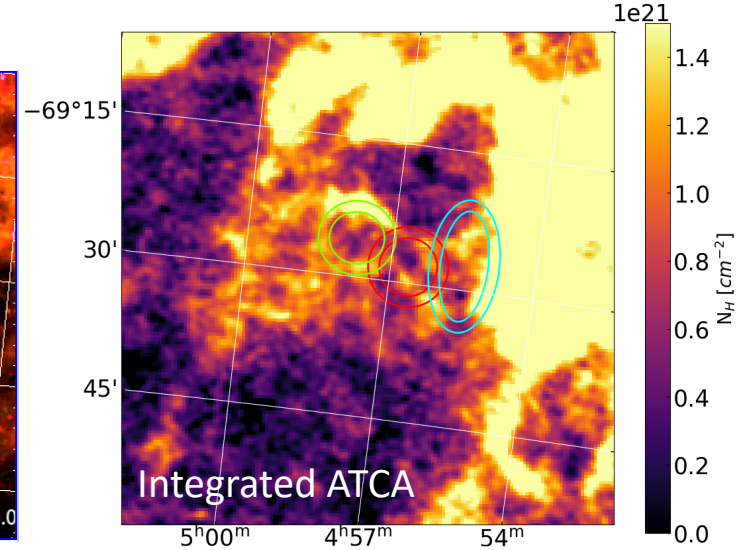
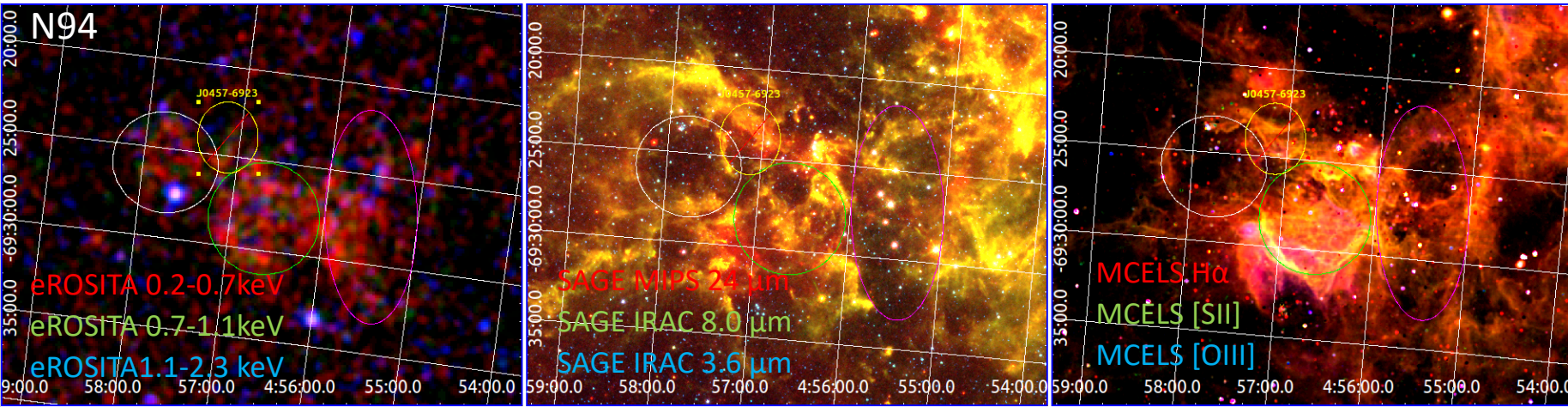
Common (or different) characteristics, physical parameters, morphologies

X-ray Observations (eROSITA): imaging + spectral fitting

Compare with the Standard Wind Bubble Model

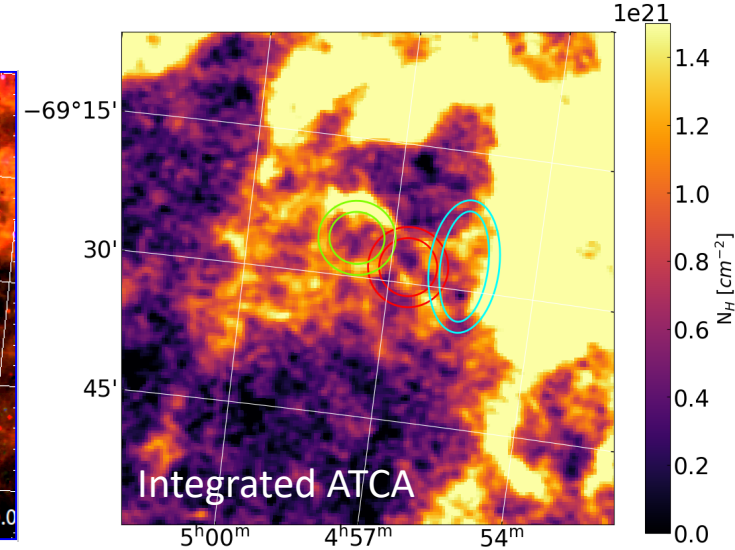
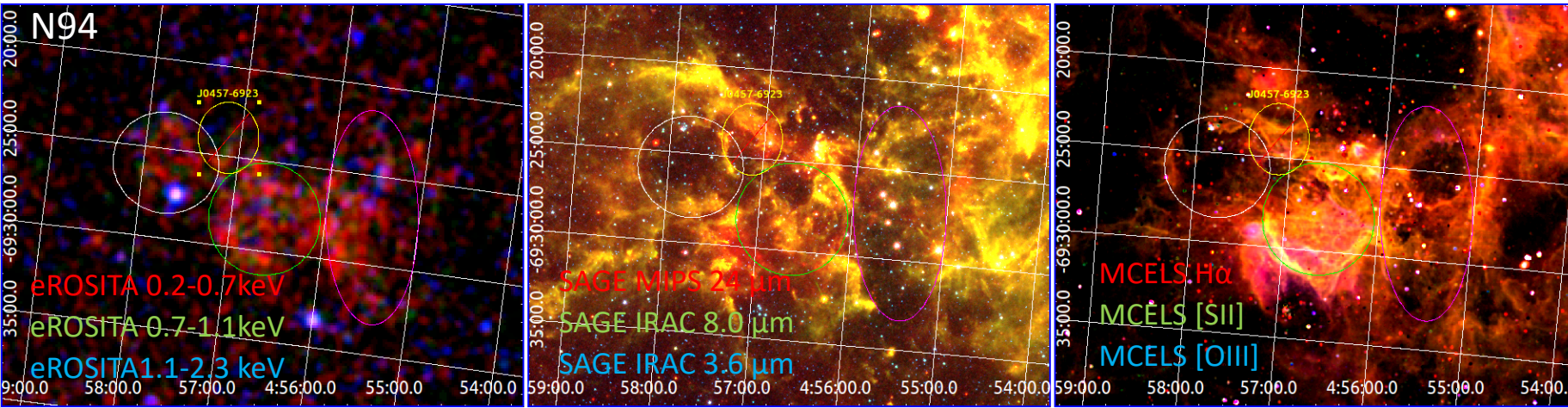
eROSITA – imaging and spectra

 **Imaging:** multiwavelength view -> region limits + environment

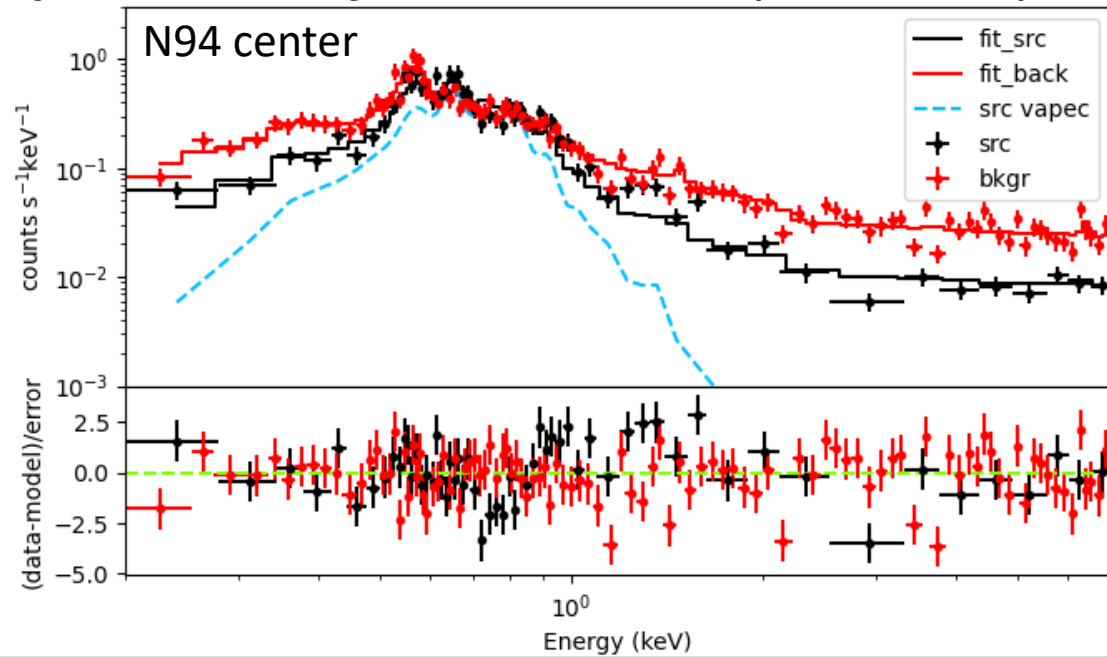


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Imaging: multiwavelength view -> region limits + environment

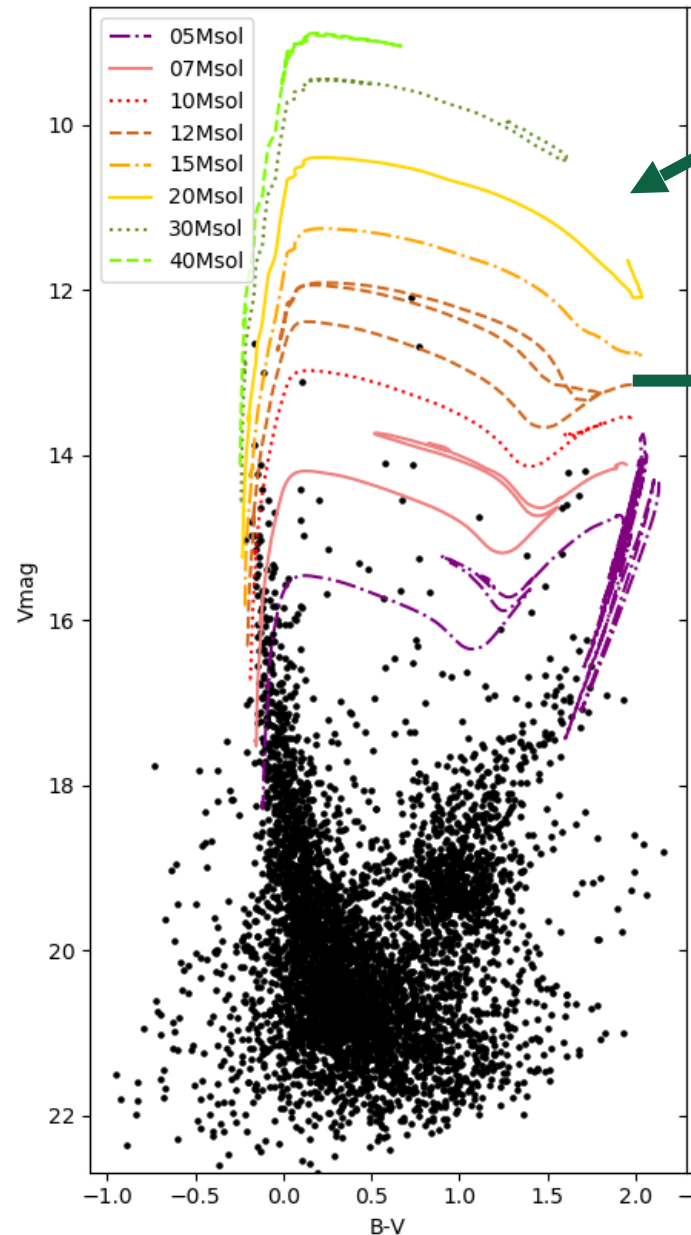


Spectral analysis: Thermal equilibrium plasma model (apec) -> Plasma properties



- kT
- L_X
- n_b
- P/k
- E_i

Standard Bubble Model – Prediction



Zaritsky et. al. (2004) stellar catalog

Number of massive stars

Estimate X ray luminosity from
stellar winds

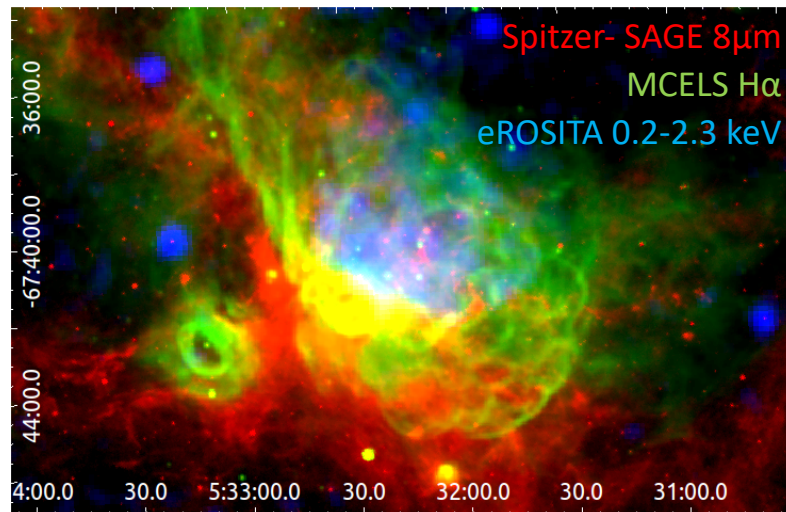
Use of Pecaut & Mamajek
(2013) table of stellar
parameters (updated 2022)

- ! L_x estimated using equations from
 - Weaver R. et. al. 1977
 - Chu et. al. 1995

Different result cases

N57: bubble explained by winds

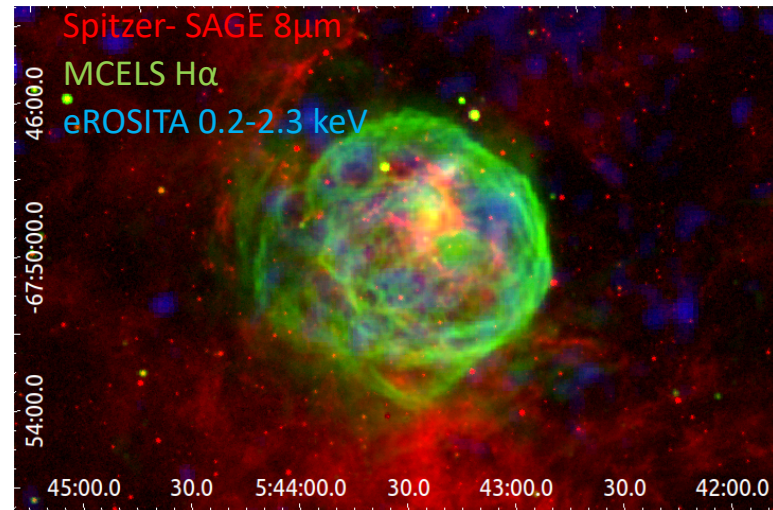
✓ $L_{Xobs} = (6.11 \pm 0.14) \cdot 10^{35} \text{ erg}$
 $L_{Xw} = (5.86 - 6.46) \cdot 10^{35} \text{ erg}$



In agreement with SB observations, predictions and previous studies of the region.

N70: bubble with X-ray excess

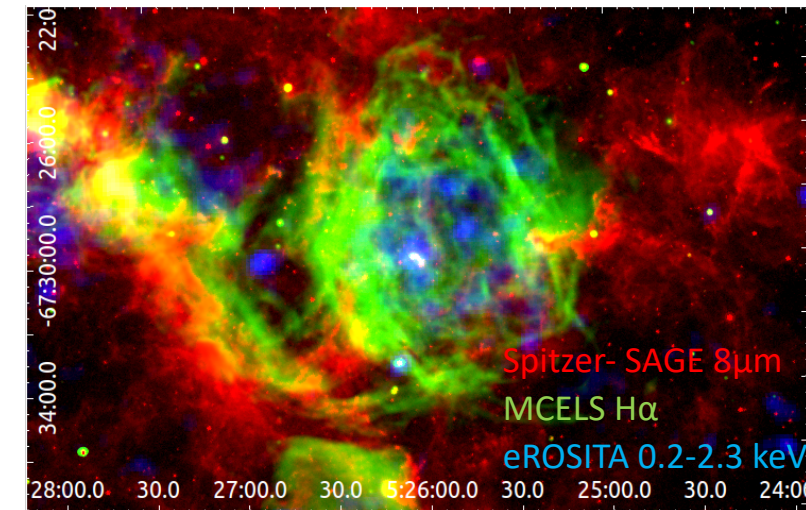
✗ $L_{Xobs} = (2.35^{+0.36}_{-0.09}) \cdot 10^{35} \text{ erg}$
 $L_{Xw} = (1.19 - 1.34) \cdot 10^{35} \text{ erg}$



Contribution from SNe: less massive stars in CMD than IMF, high [SII] vs Hα.

N51D: bubble lacking Xrays

✗ $L_{Xobs} = (3.05^{+0.11}_{-0.10}) \cdot 10^{35} \text{ erg}$
 $L_{Xw} = (5.63 - 8.97) \cdot 10^{35} \text{ erg}$

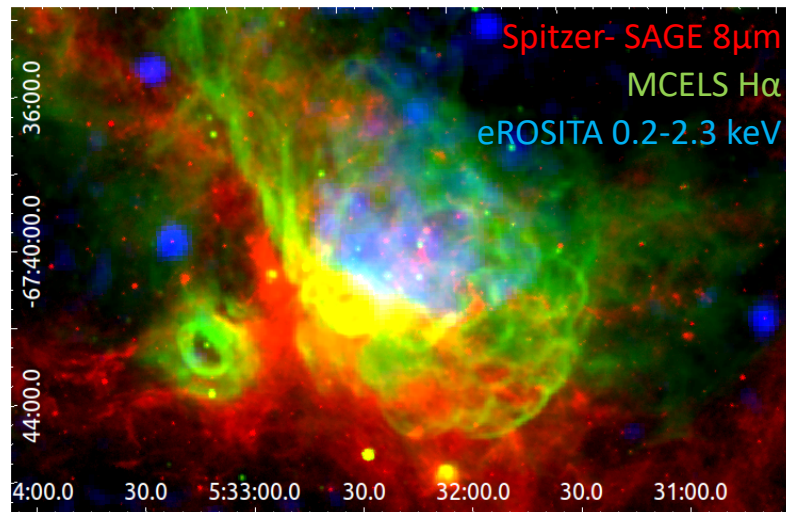


Observed luminosity is smaller than expected. E loss in interface layers, outflow, transmission to cosmic rays.

Different result cases

N57: bubble explained by winds

✓ $L_{Xobs} = (6.11 \pm 0.14) \cdot 10^{35} \text{ erg}$
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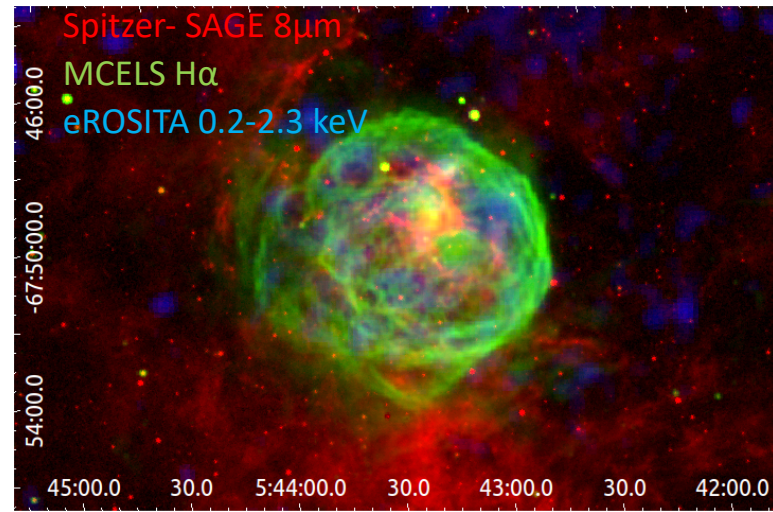


$$kT = 0.18 \pm 0.01 \text{ keV}$$

In agreement with SB observations, predictions and previous studies of the region.

N70: bubble with X-ray excess

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 $L_{Xw} = (1.19 - 1.34) \cdot 10^{35} \text{ erg}$

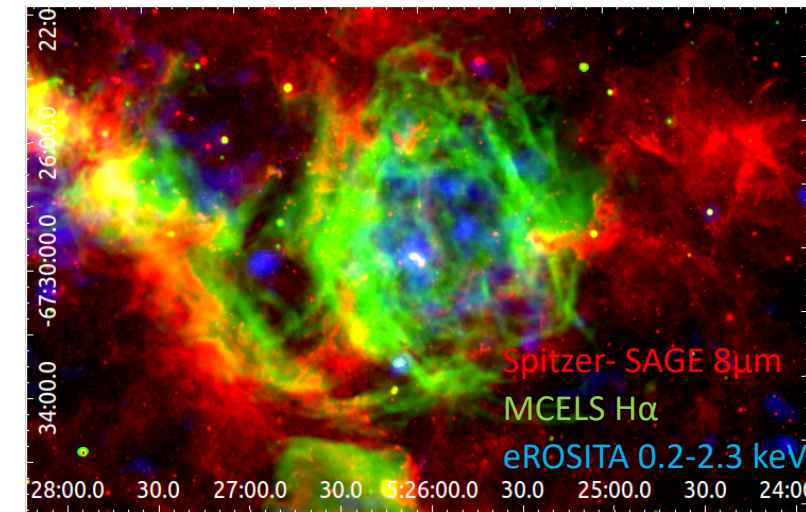


$$kT = 0.22 \pm 0.01 \text{ keV}$$

Contribution from SNe: less massive stars in CMD than IMF, high [SII] vs H α .

N51D: bubble lacking Xrays

✗ $L_{Xobs} = (3.05^{+0.11}_{-0.10}) \cdot 10^{35} \text{ erg}$
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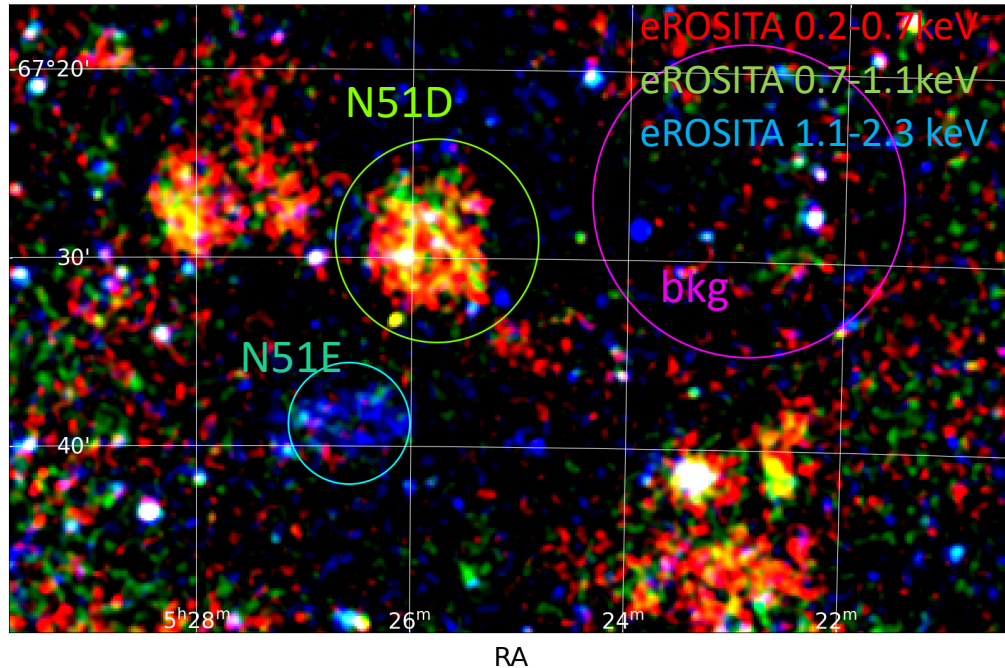


$$kT = 0.21 \pm 0.01 \text{ keV}$$

Observed luminosity is smaller than expected. E loss in interface layers, outflow, transmission to cosmic rays.

Different result cases

Unexpected find: N51E (DEML196) the “blue” sheep



- Visible exclusively in the 1.1-2.3 keV band
- The spectral analysis is not enough to disentangle between a thermal or non-thermal nature.

$$kT = 4.45^{+0.73}_{-0.75} \text{ keV}$$

$$L_{Xobs} = (0.90 \pm 0.04) \cdot 10^{35} \text{ erg}$$

$$L_{Xw} = (0.91 - 1.63) \cdot 10^{35} \text{ erg}$$

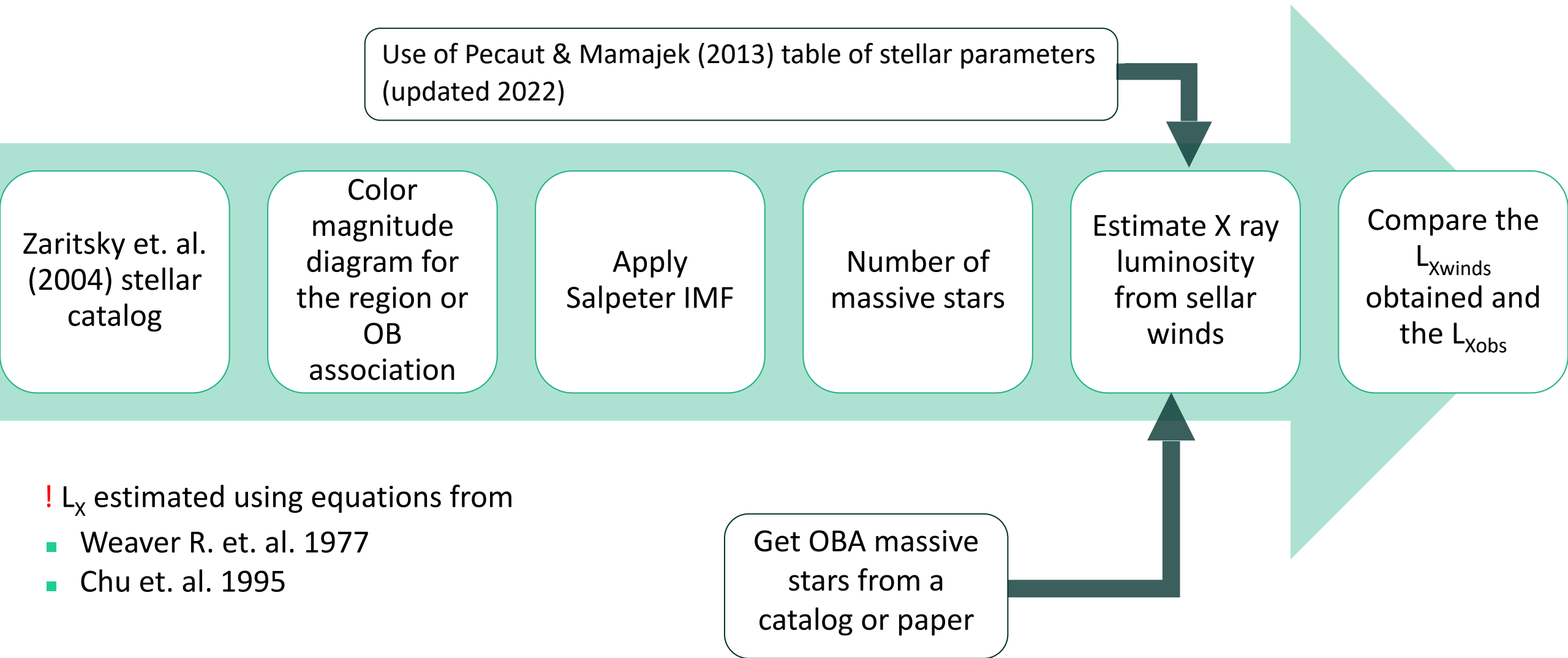
WORK IN PROGRESS!!!

Summary

- ❑ Thanks to the nature of eROSITA data we are able to perform a systematic study of HII regions in the Magellanic Clouds
- ❑ X-ray luminosity from Observations vs Standard Wind Bubble model
 - ❑ Inside expected range -> X-ray luminosity explained by stellar population
 - ❑ More than expected -> Contribution from SNe
 - ❑ Less than expected -> Absorption of X-rays by gas, dust and cosmic rays, energy used for cooling, less MS than estimated.
- ❑ We detect unusual X-ray emission in N51E
 - ❑ almost exclusively in 1.1-2.3keV.
 - ❑ The spectral analysis results inconclusive for both a thermal and non-thermal model.

BACKUP SLIDES

Standard Bubble Model – Prediction



Stellar feedback – Luminosity from winds

STANDARD MODEL – Weaver et al (1977)

□ Mechanical luminosity from winds:

$$L_W = \sum_i \frac{1}{2} \dot{M}_{W,i} v_{W,i}^2$$

□ With L_W , assuming n_0 and knowing R : bubble age

$$R = (42 \text{ pc}) L_{W,37}^{1/5} n_0^{-1/5} t_6^{3/5} \quad V = \frac{dR}{dt} = (0.59 \text{ km/s}) \frac{R_{pc}}{t_6}$$

□ Finally, X ray luminosity (Chu et. al (1995)):

$$L_X = 1.1 \cdot 10^{35} I(\tau) \xi L_{W,37}^{33/35} n_0^{17/35} t_6^{19/35}$$

$$I(\tau) = \frac{125}{33} - 5\tau^{1/2} + \frac{3}{5}\tau^3 - \frac{5}{11}\tau^{11/3}$$

$$\tau = 0.16 L_{W,37}^{-8/35} n_0^{-2/35} t_6^{6/35}$$

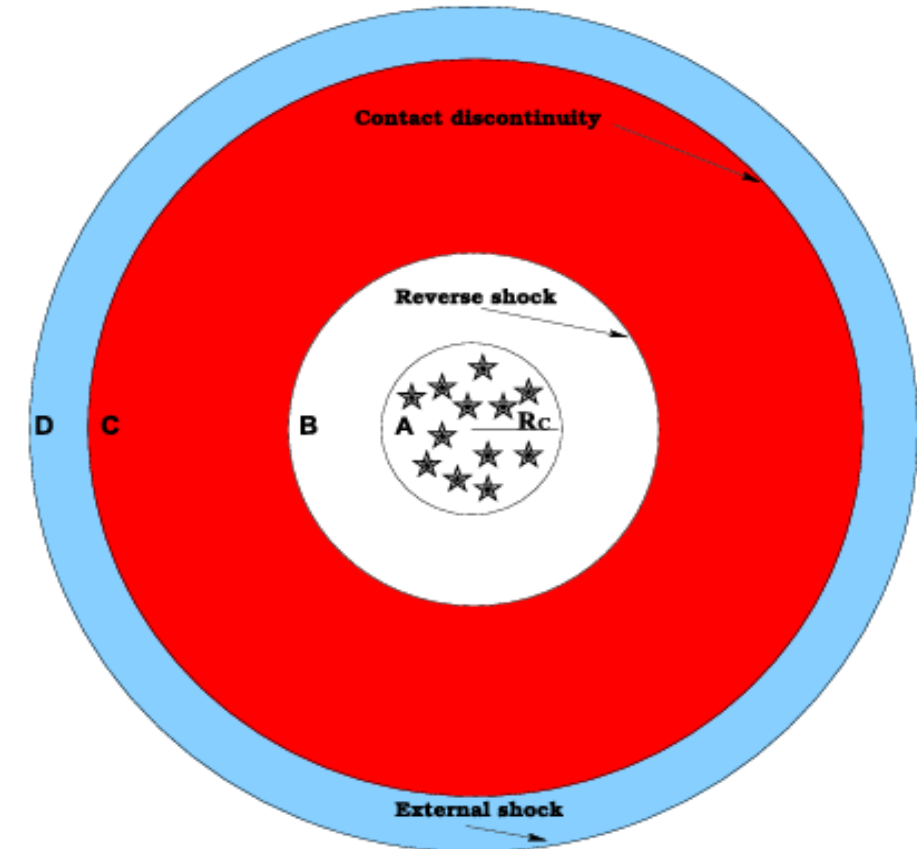


Figure 1. Generalization of the standard model (Weaver et al. 1977) conceived for a single star. Schematic structure of a SB produced by an OBA: (A) star cluster region, (B) free-wind region, (C) shocked-wind region, and (D) shocked-ISM region.

From Reyes-Iturbide et. al. 2014

Parameters from X-ray spectra:

❑ Flux – Luminosity

$$L = 4\pi F d^2$$

❑ From the norm-> estimate bubble gas density

$$n = 4.8 \cdot 10^{30} \sqrt{\frac{norm}{fV}}$$

❑ Estimate pressure

$$\frac{P}{k} = 2.31 n f^{-1/2} T$$

❑ Thermal energy of the bubble

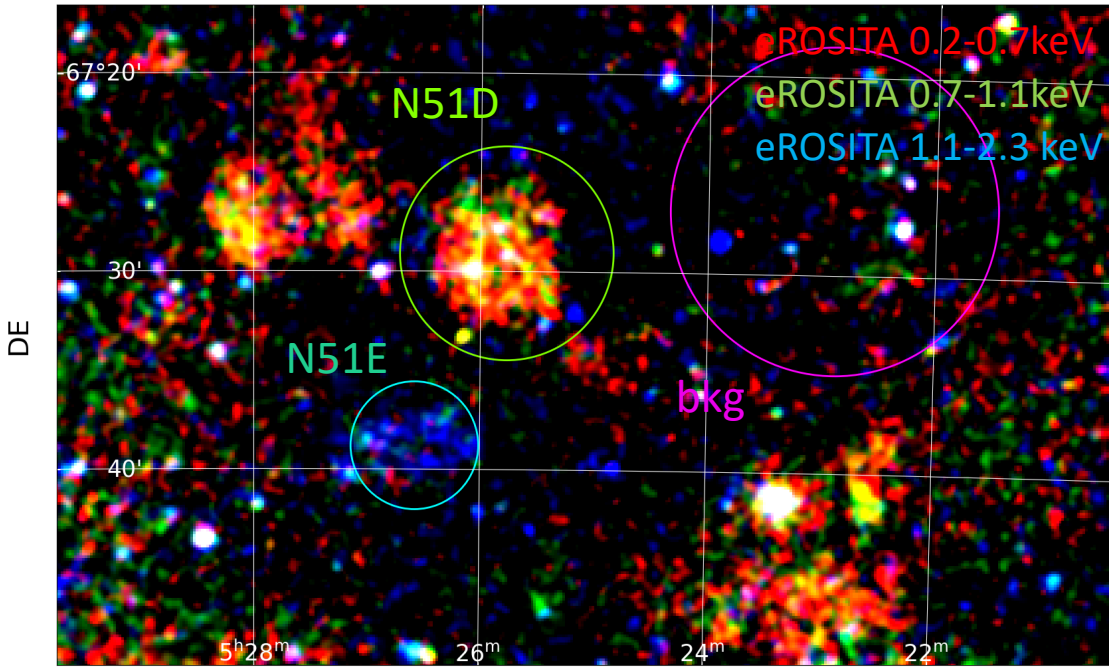
$$E = \frac{3}{2} P f V$$

❑ Gas mass inside of the bubble

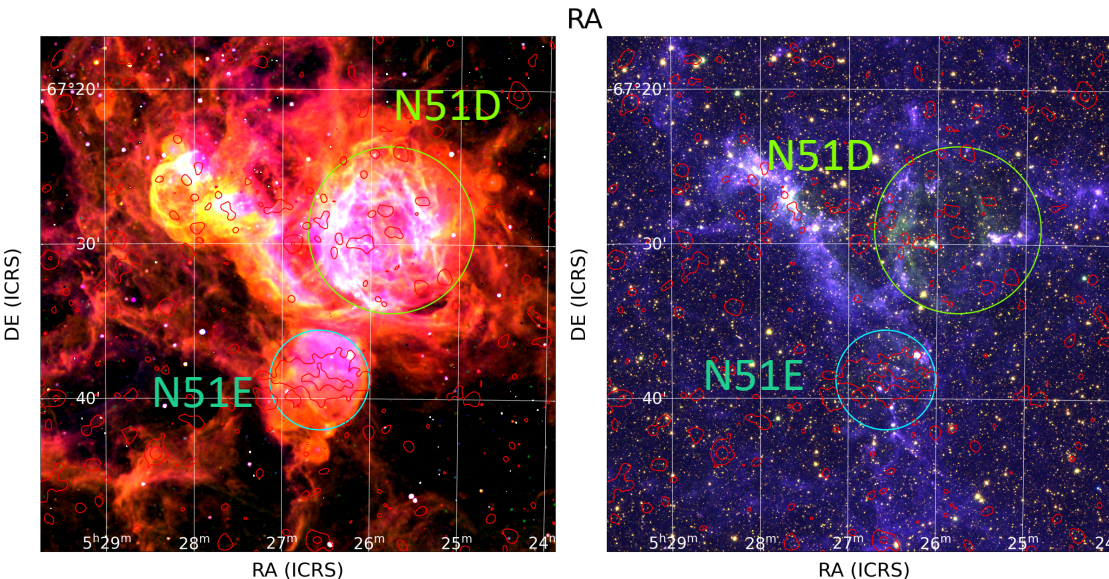
$$M_B = 2.31 n \mu m_H V$$

Note: young bubbles are usually associated with a filling factor of $f=1$

N51E (DEM L196)-the black sheep



- Visible exclusively in the 1.1-2.3 keV band
- No intense star formation
- No WR star
- From NH data -> not due to absorption
- There is no clear sign of a SNe going off
- The spectral analysis is not enough to disentangle between a thermal or non-thermal nature.

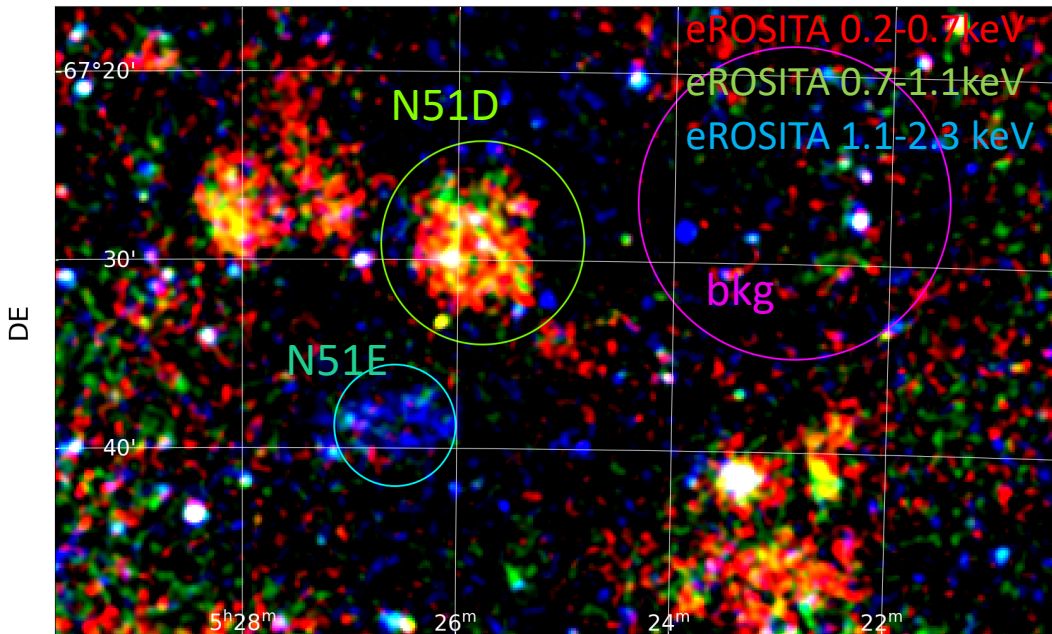


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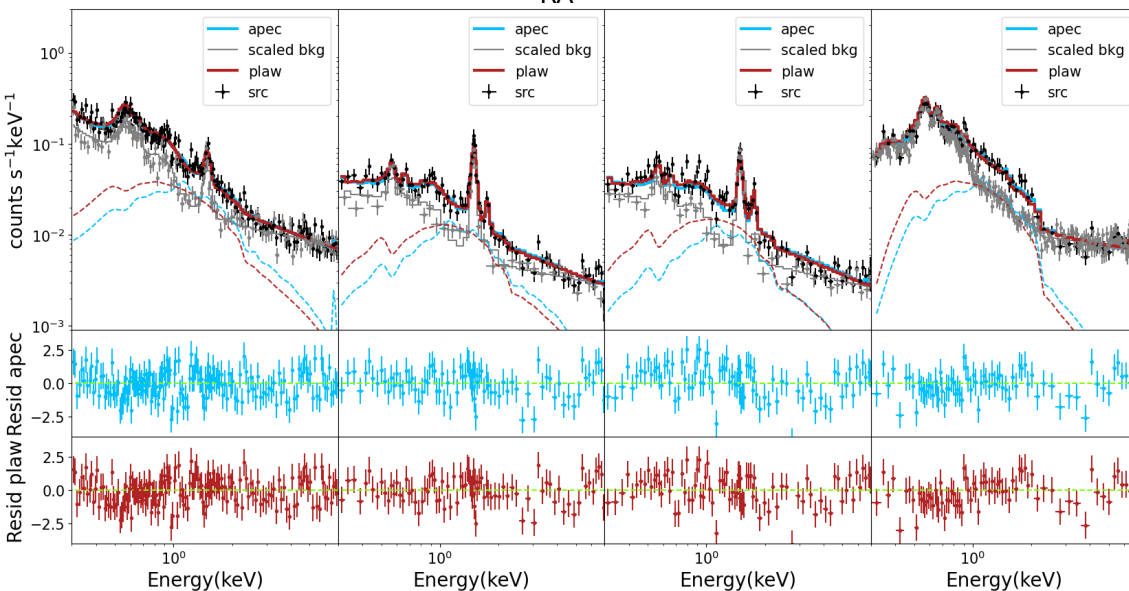
$$L_{Xw} = (0.91 - 1.63) \cdot 10^{35} \text{ erg}$$

$$kT = 4.45^{+0.73}_{-0.75} \text{ keV}$$

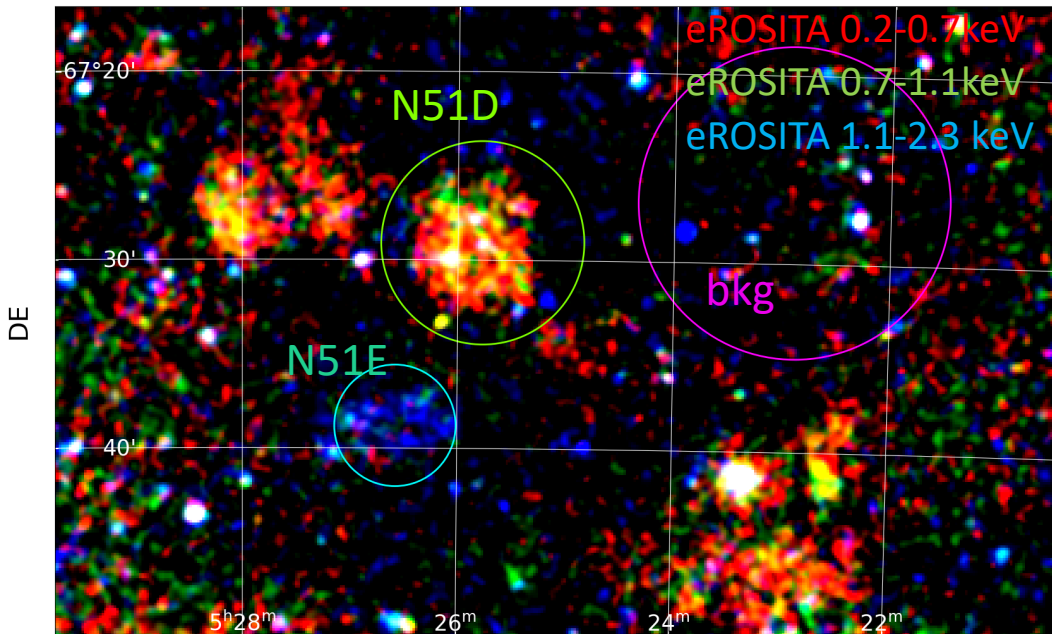
N51E (DEM L196)-the “blue” sheep



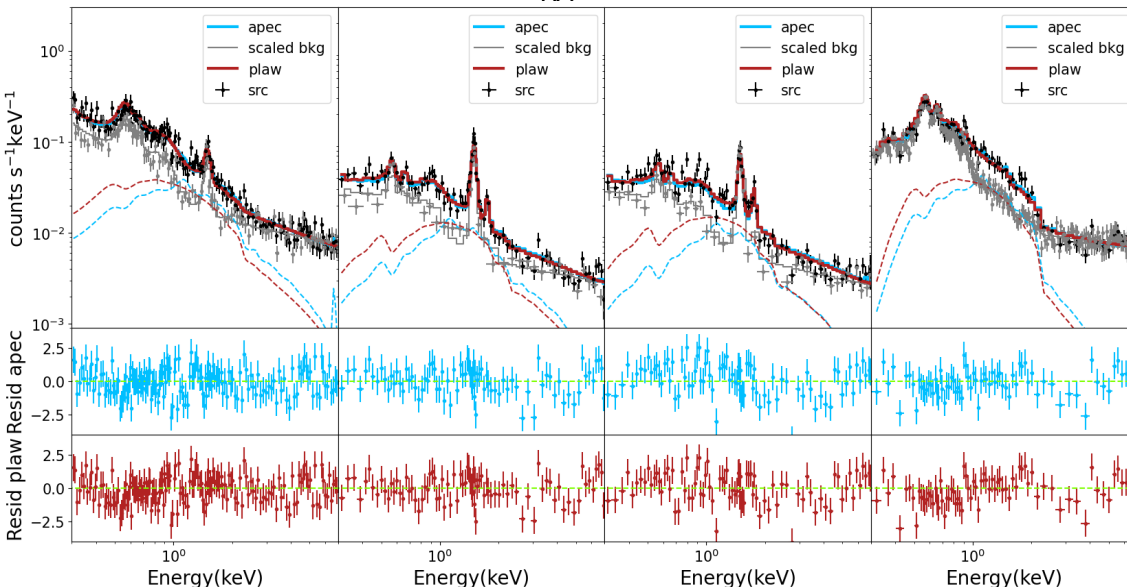
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N70 (DEM L301)

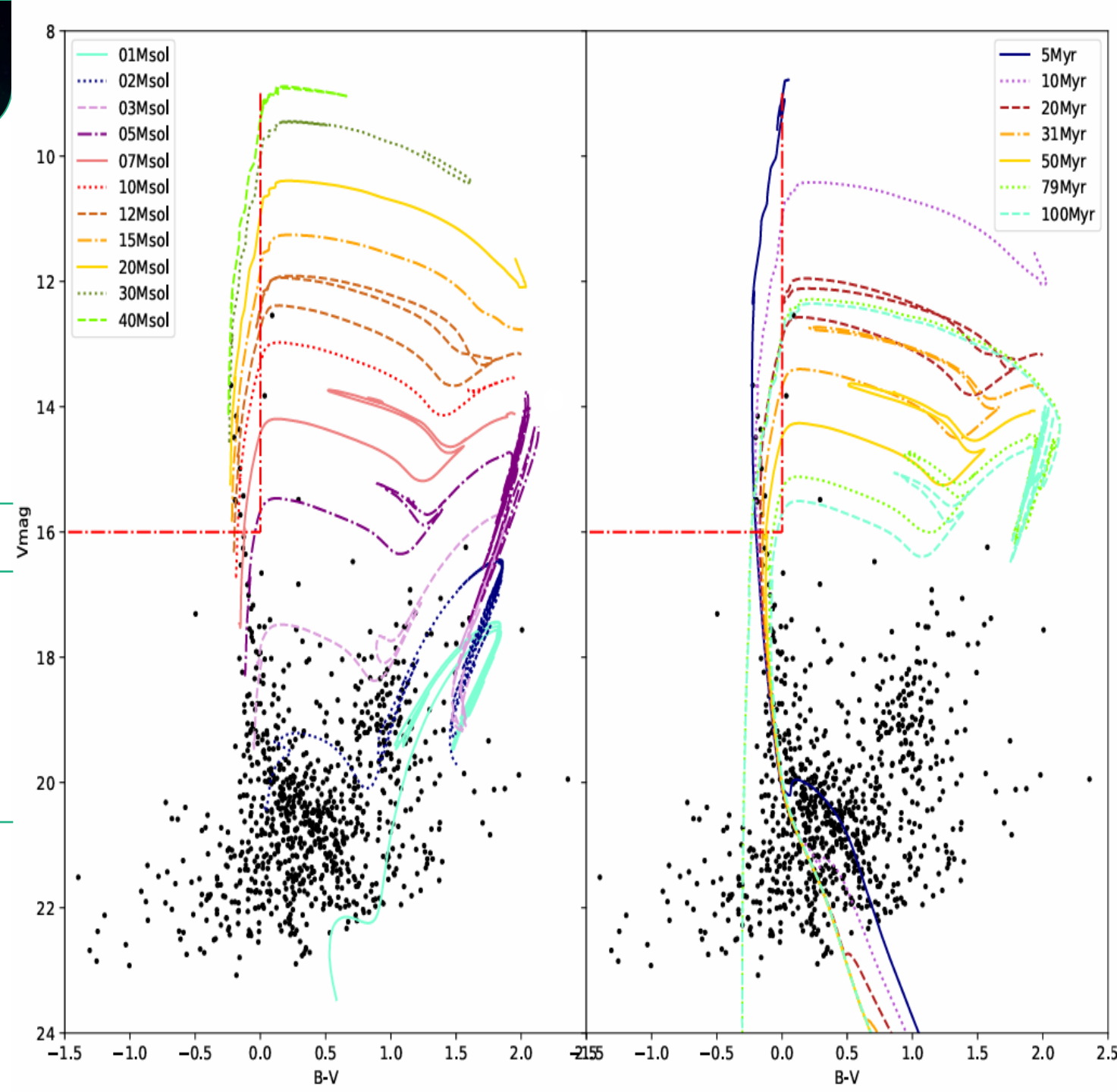
Using the CMD and OB winds

Cluster : $t_{cl} \sim 5 \text{ Myr}$

Note: assuming ambient density $n_0 = 0.16 \text{ cm}^{-3}$
(Rosado et al 1981)

	IMF (7-10 $M_{\odot}$ range)	Stars (Oey 1996)
$L_w \text{ (erg/s)}$	$6.21\text{-}7.12 \cdot 10^{37}$	$7.12 \cdot 10^{37}$
$L_x \text{ (erg/s)}$	$1.19\text{-}1.34 \cdot 10^{35}$	$1.34 \cdot 10^{35}$
$t_B \text{ (Myr)}$	0.55-0.53	0.53
$M_w (M_{\odot})$	252-277 (5Myr)	100 (5Myr)

$\sim 1 \text{ SN in the HII region}$



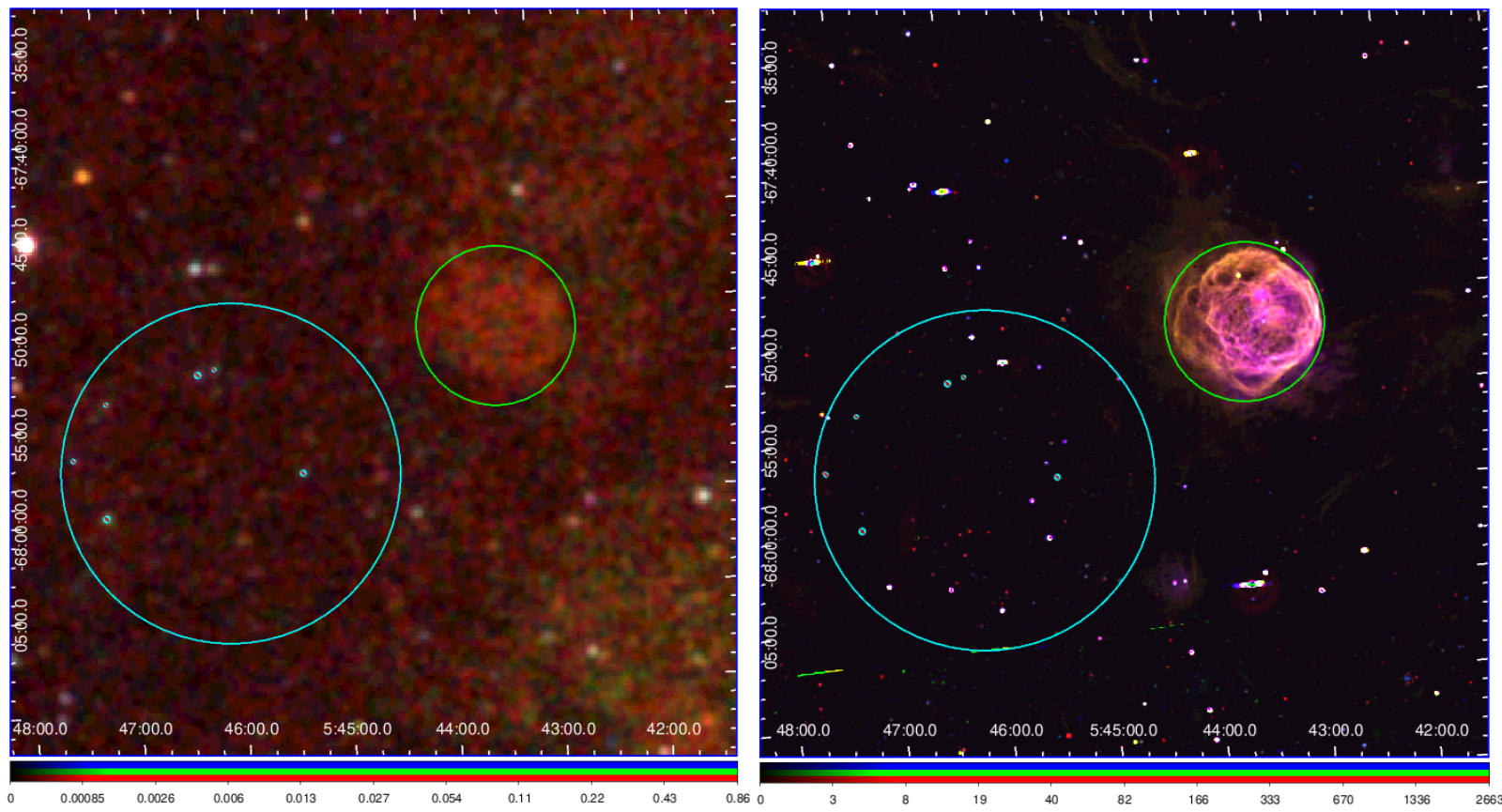
N70 (DEM L301)

- Well described in previous studies by an absorbed plasma model

$$\text{TBabs} * \text{TBvarabs} * \text{vapec}$$

eROSITA RGB (0.2-0.7, 0.7-1.1, 1.1-2.3 keV)

MCELS RGB (H, SII, OIII)



Green: source region
Cyan: Background region

N70 (DEM L301)

Using the eROSITA spectra

From fit

$$N_H < 2.61 \cdot 10^{20} \text{ cm}^{-2}$$

$$\text{norm} = 6.87^{+0.5}_{-1.7} \cdot 10^{-4}$$

$$kT = 0.22 \pm 0.01 \text{ keV}$$

$$\log F_x = -12.10^{+0.06}_{-0.02} \text{ erg/cm}^2 \text{ s (0.2 to 5 keV)}$$

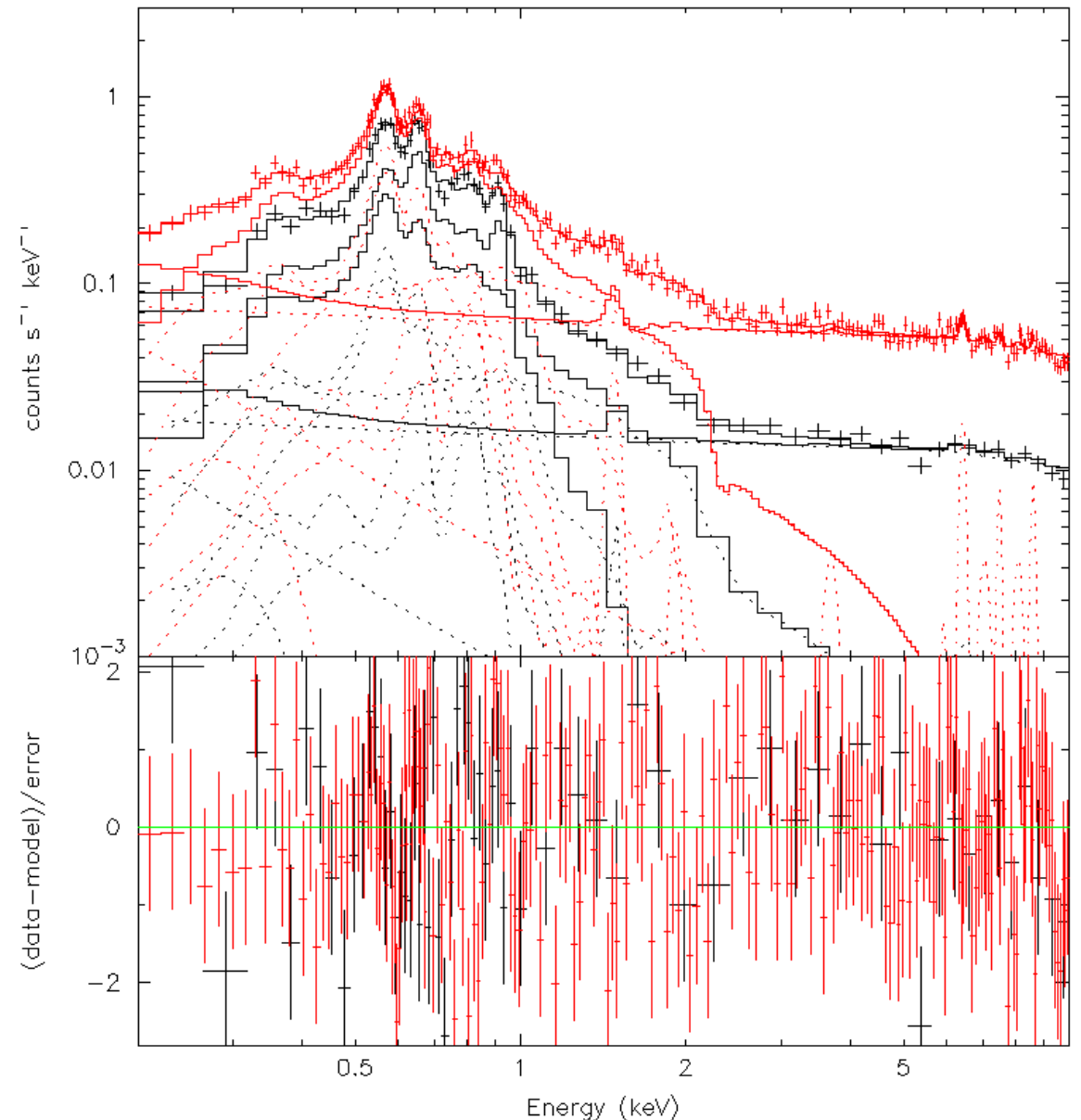
$$P/k = 1.42 \pm 0.05 \cdot 10^4 \text{ cm}^{-3} \text{ K}$$

$$n = 2.37 \pm 0.01 \cdot 10^{-2} \text{ cm}^{-3}$$

$$E_{\text{th}} = 8.26^{+0.26}_{-0.29} \cdot 10^{49} \text{ erg}$$

$$M_B = 828^{+5}_{-2} M_{\odot}$$

$$L_x = 2.35^{+0.36}_{-0.09} \cdot 10^{35} \text{ erg/s}$$



N70 (DEM L301)

From different studies (using XMM-Newton)

	N_H (10^{22}cm^{-2})	kT (keV)	F_x 10^{-12} erg $\text{cm}^{-2}\text{s}^{-1}$	L_x 10^{35} erg	Range
Zhang et al 2014	0.31	0.19	2.17	6.12	0.4-1.3 keV
De Horta et al 2014 vapec	0.05	0.248		2.7	0.2-5.0 keV
apec	0.014	0.255		2.2	0.2-5.0 keV
vpshock	0	0.256		1.8	0.2-5.0 keV
Reyes Iturbide 2014	0.05	0.22	0.7	2.4	0.2-1.1keV
My fit (eROSITA)	0.06	0.22	0.78	2.35	0.2-5.0keV

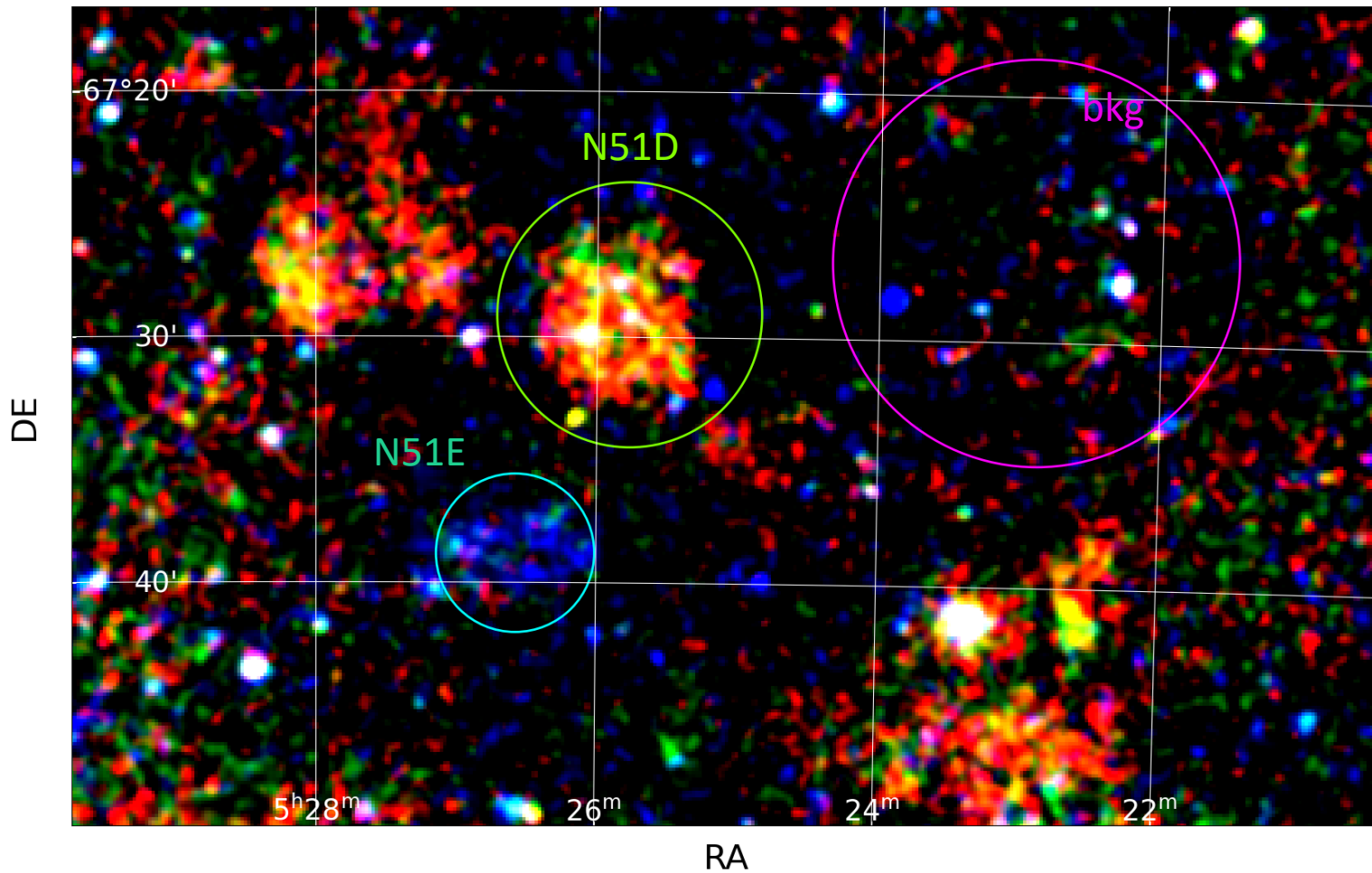
- ❑ Zhang et al 2014 : phabs*apec
- ❑ Reyes-Iturbide et al 2014: absorbed apec model
- ❑ de Horta et al 2014: phabs +additional absorption column model + apec, vapec and vpshock
- ❑ My model: TBabs*TBvarabs*vapec

Summary of regions (as of June 2026)

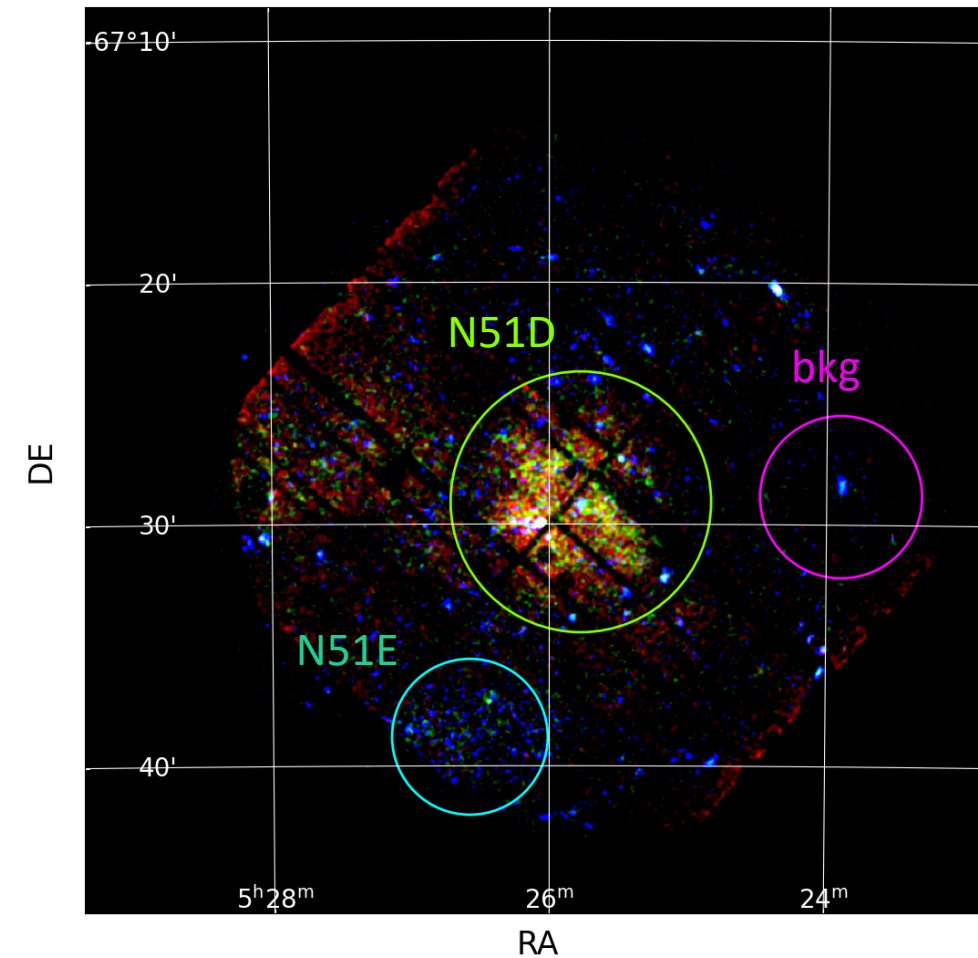
Region	N_H (10^{22}cm^{-2})	kT (keV)	Lx spec 10^{35} erg	Lx stars 10^{35} erg
N70	<0.03			1.19-1.34
N51D	0.08			5.63-8.97
N51E	0.1837 (HI4PI)			0.91-1.63
N57				5.86-6.46
N94 left	0.071 (HI4PI)			1.15-1.39
N94 center	0.0728 (HI4PI)			1.41-2.04
N94 right	0.1139 (HI4PI)			4.51-6.25
N185	<0.07			0.20-0.21

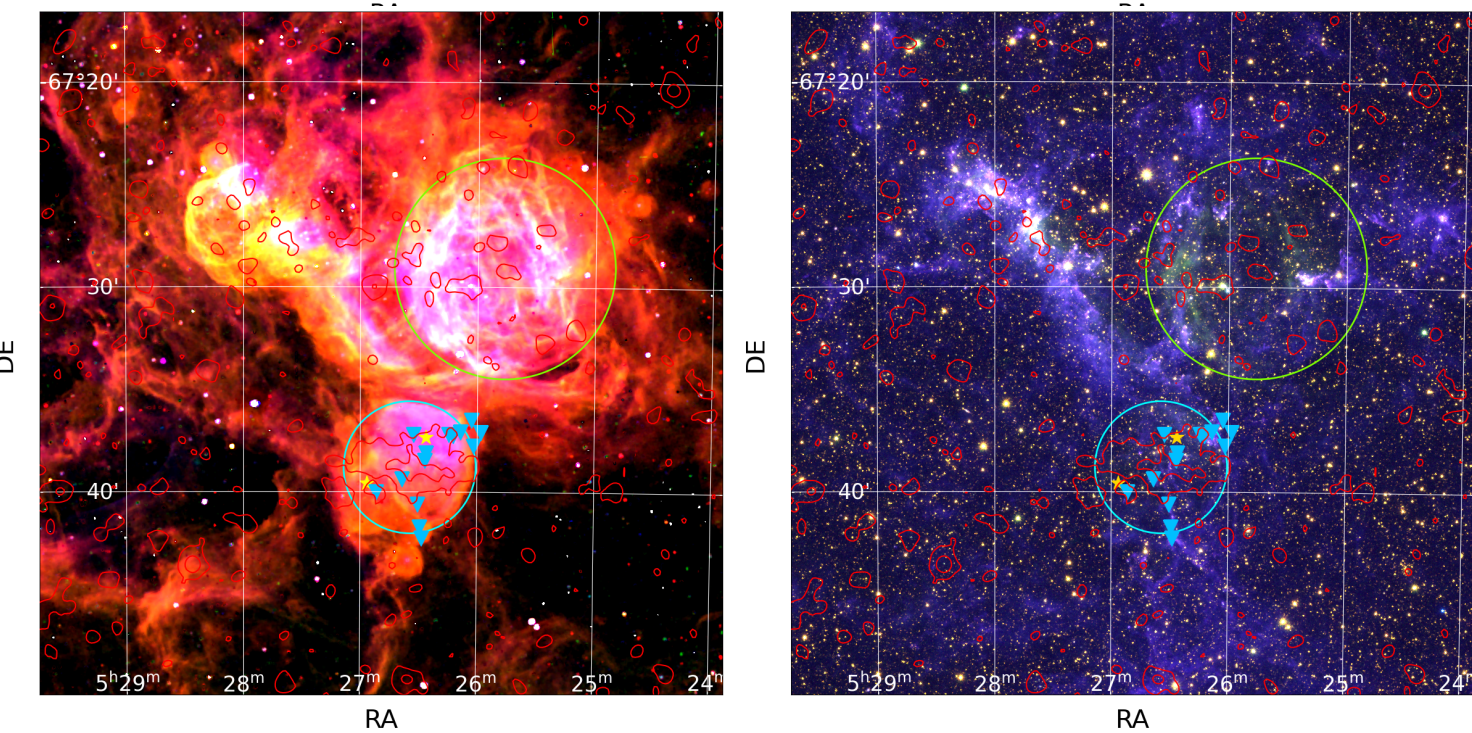
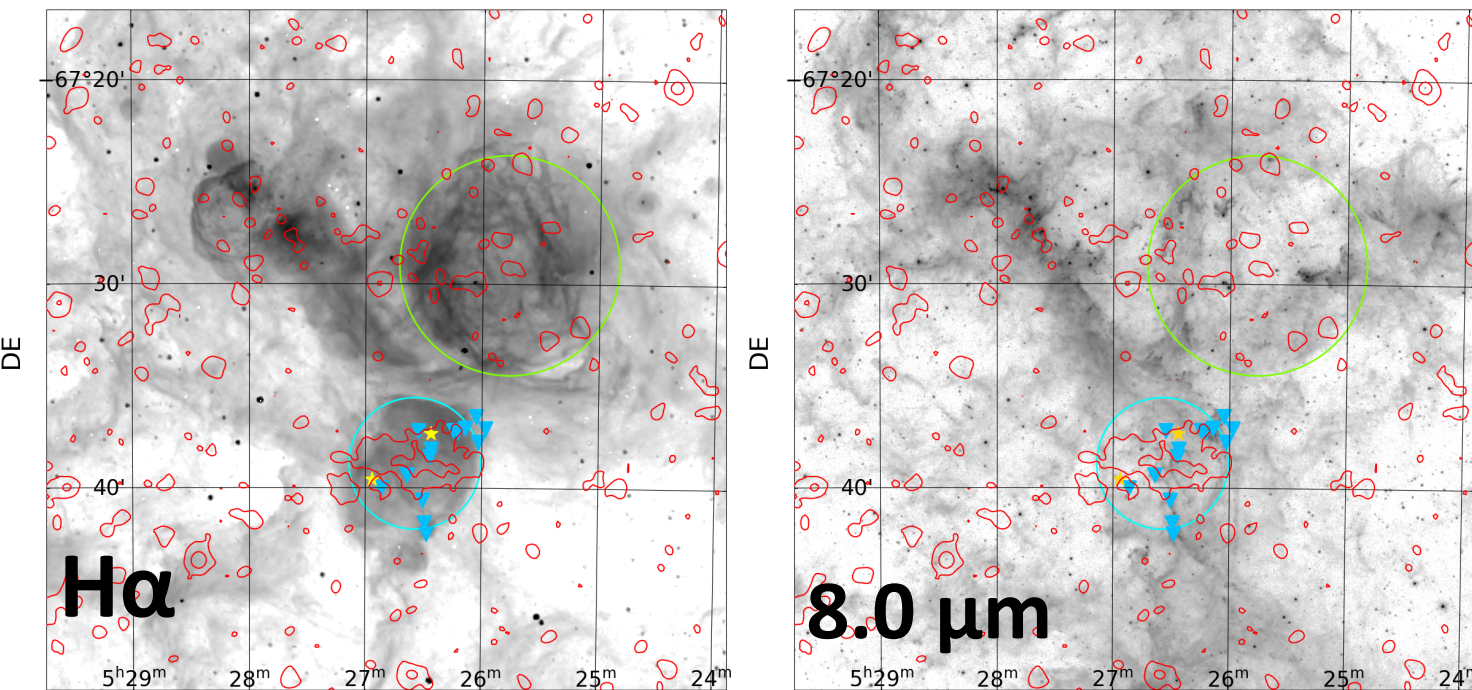
N51E (DEM L196)

eROSITA RGB (0.2-0.7, 0.7-1.1, 1.1-2.3 keV)

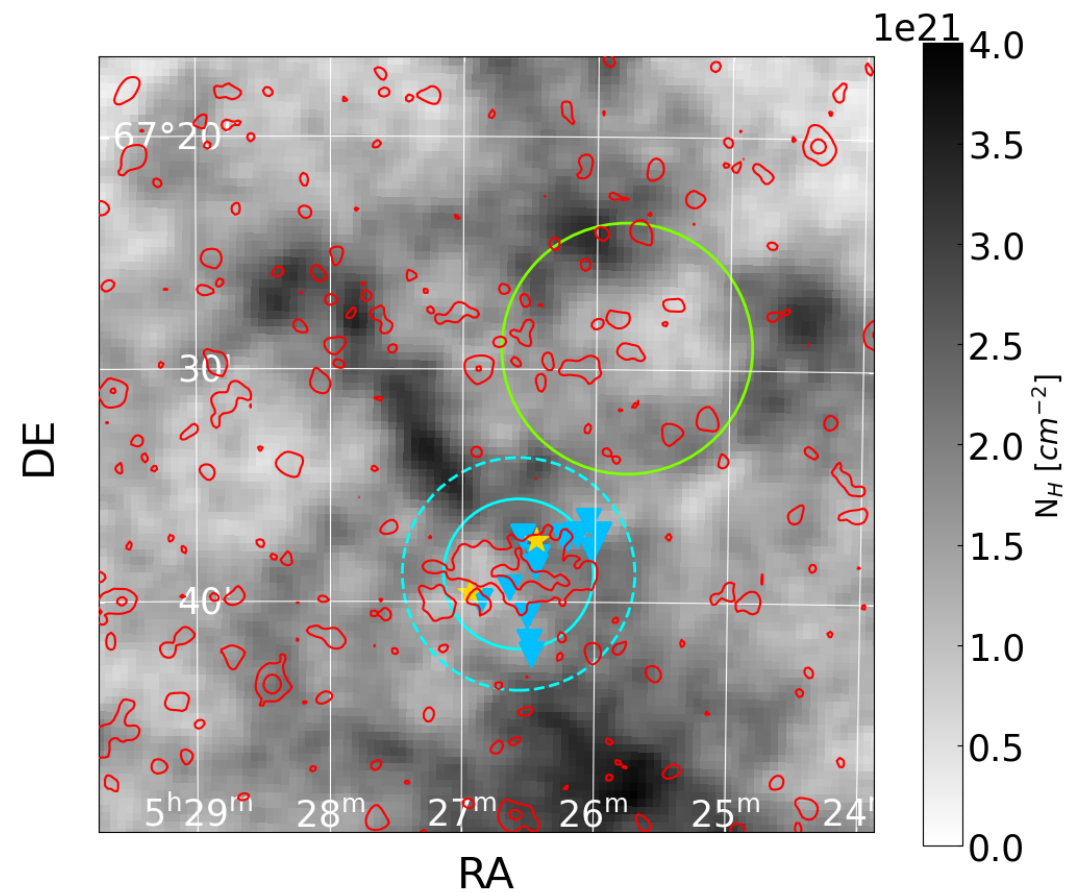


XMM-Newton RGB (0.2-0.7, 0.7-1.1, 1.1-3.0 keV)

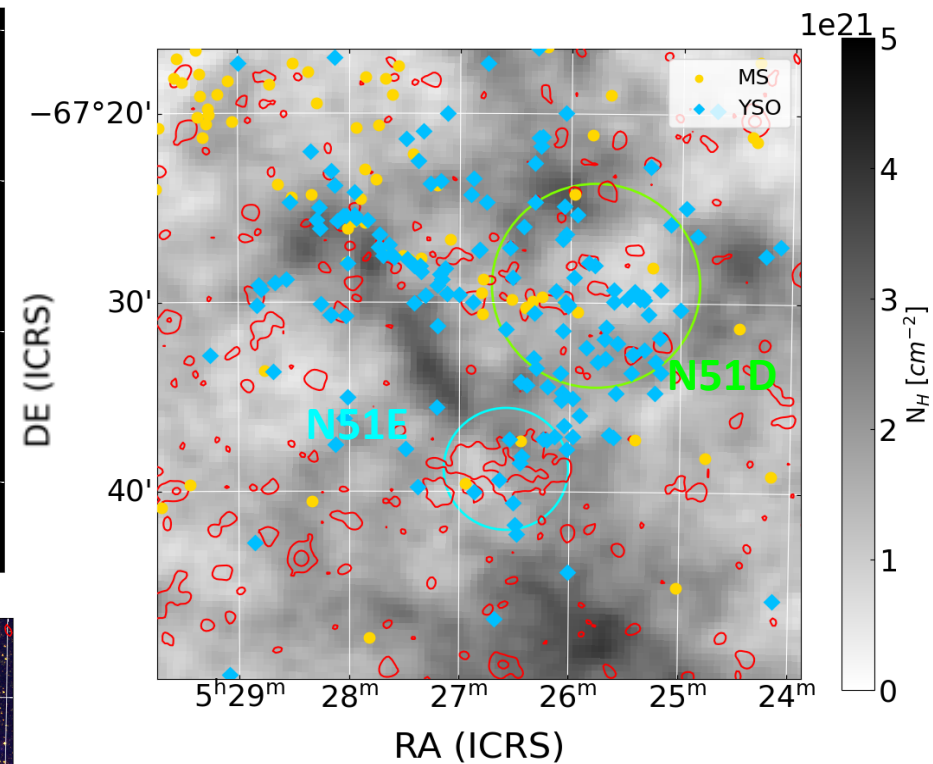
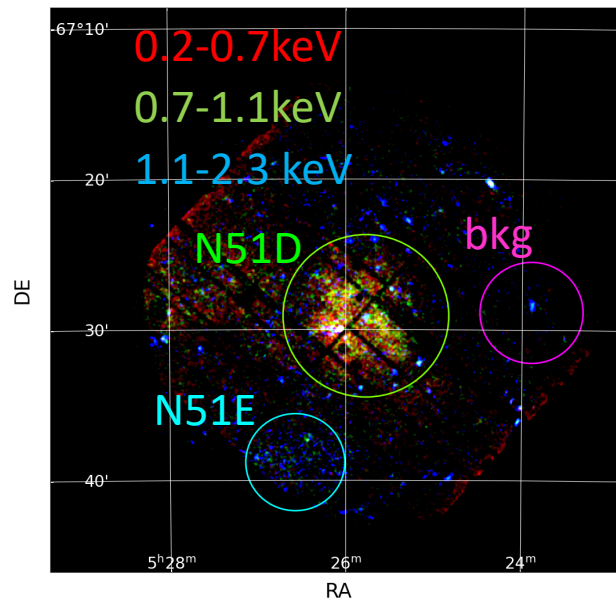
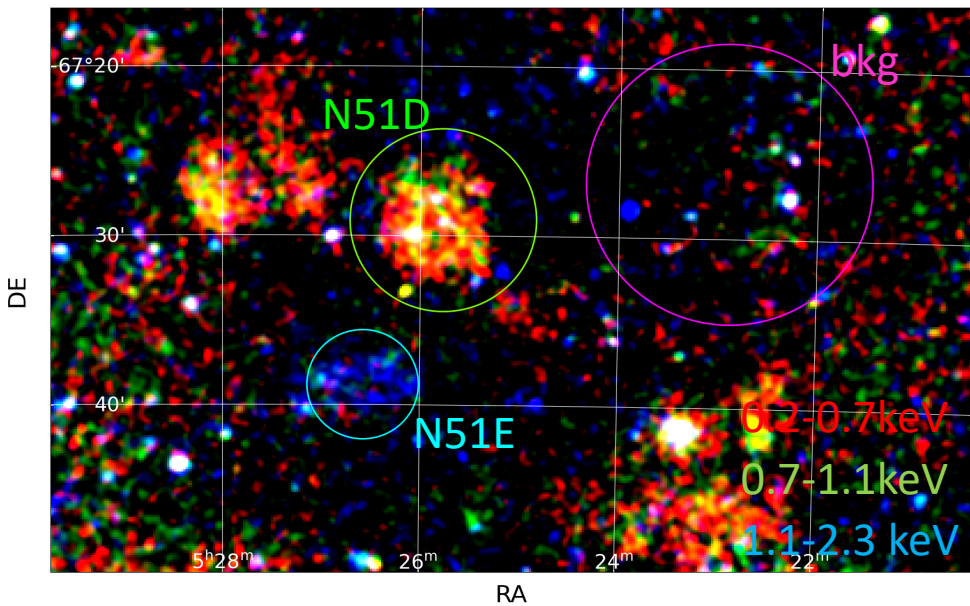




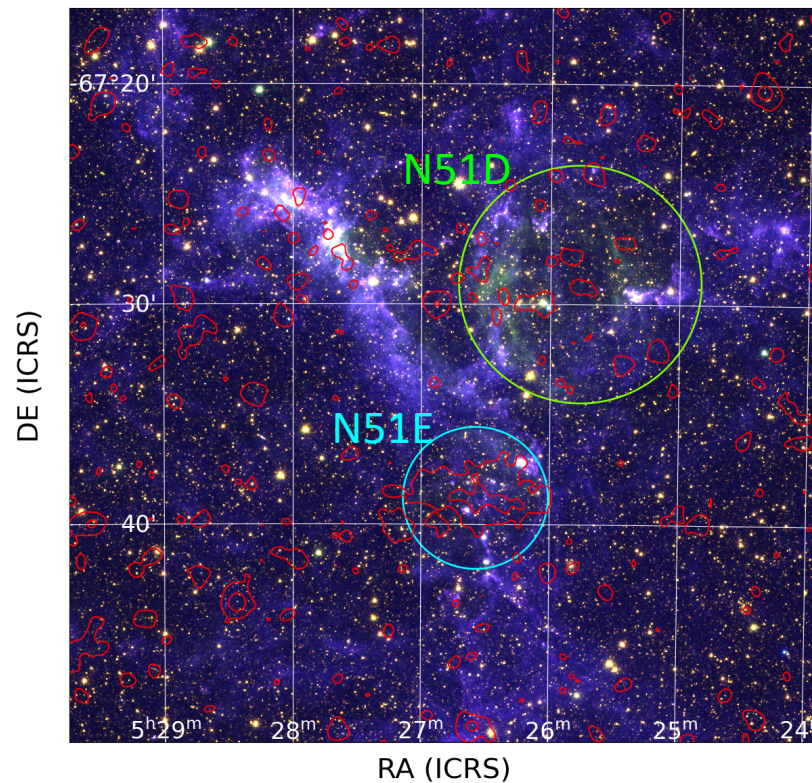
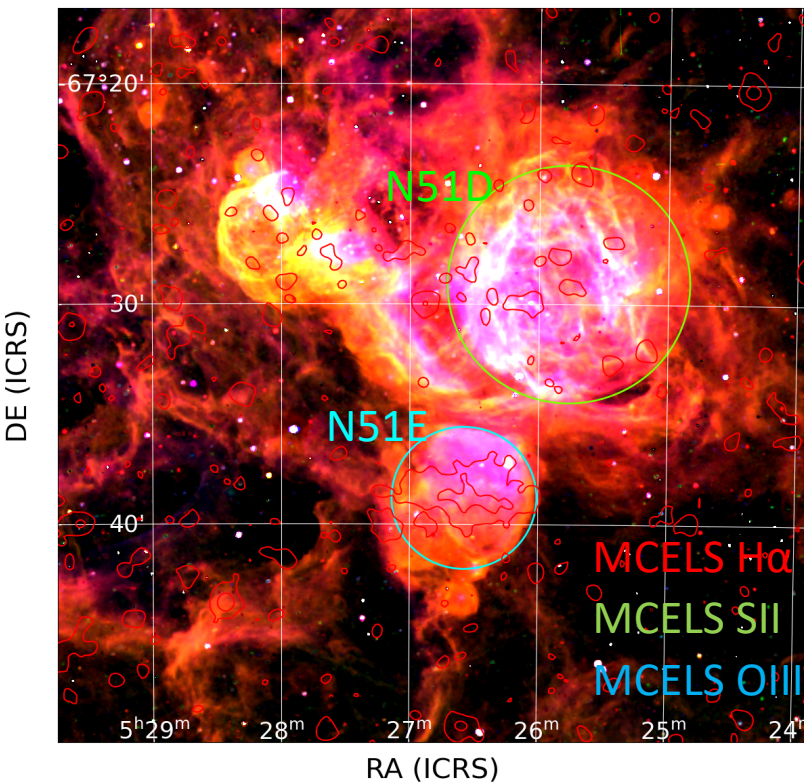
ATCA HI integrated (200-350 km/s)



- Mean $N_H = 1.98 \cdot 10^{21} \text{ cm}^{-2}$
- LMC depth: 3.44 kpc (Subramanian+2009)
- Ambient density $n_0 = 0.19 \text{ cm}^{-3}$



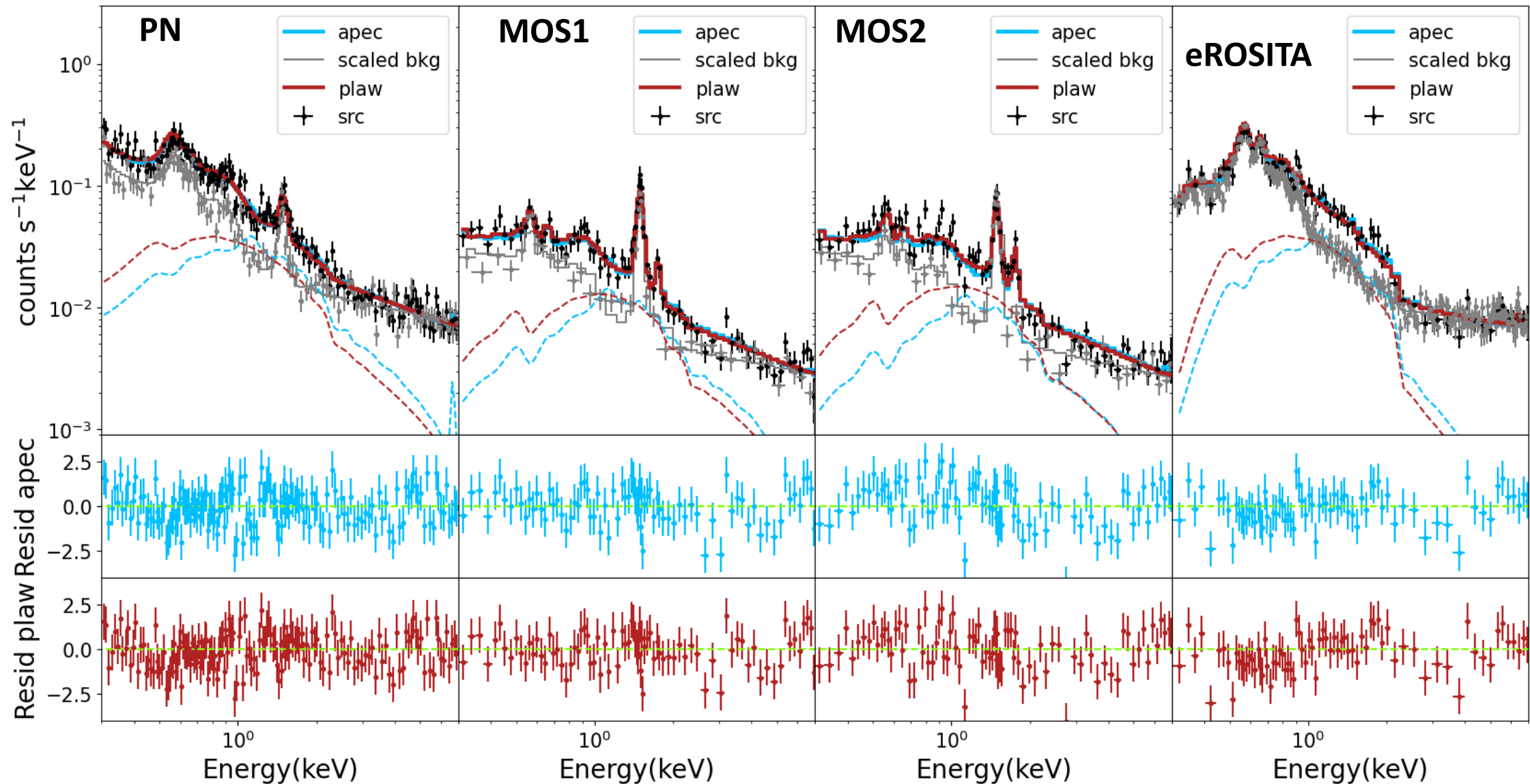
ATCA HI integrated (200-350 km/s)



- Mean $N_H = 1.98 \cdot 10^{21} \text{ cm}^{-2}$
- LMC depth: 3.44 kpc (Subramanian+2009)
- Ambient density $n_0 = 0.19 \text{ cm}^{-3}$

N51E (DEM L196)

eROSITA and XMM simultaneous fit with scaled background



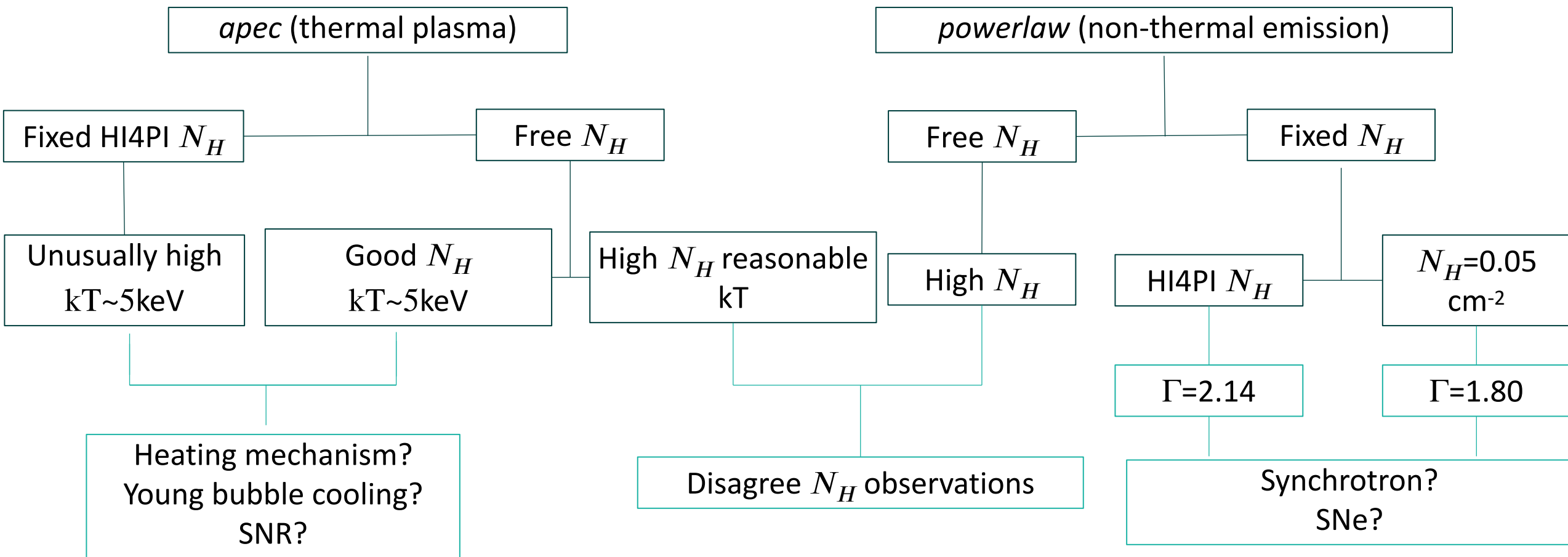
N51 (DEM L196)

eROSITA and XMM simultaneous fit

par	vapec			plaw		
	high T	low T	HI4PI N_H	nonfix N_H	HI4PI N_H	fix low N_H
N_H	$0.065^{+0.040}_{-0.044}$	$1.69^{+0.10}_{-0.10}$	0.1837	$0.99^{+0.20}_{-0.23}$	0.1837	0.05
kT	$5.29^{+0.65}_{-0.94}$	$0.78^{+0.04}_{-0.04}$	$4.45^{+0.73}_{-0.75}$	-	-	-
Γ	-	-	-	$3.77^{+0.35}_{-0.44}$	$2.14^{+0.10}_{-0.10}$	$1.80^{+0.09}_{-0.09}$
norm	$2.65^{+0.19}_{-0.20} \cdot 10^{-4}$	$5.67^{+0.73}_{-0.64} \cdot 10^{-4}$	$2.79^{+0.18}_{-0.19} \cdot 10^{-4}$	$2.26^{+0.60}_{-0.61} \cdot 10^{-4}$	$7.45^{+0.61}_{-0.61} \cdot 10^{-5}$	$6.05^{+0.52}_{-0.51} \cdot 10^{-5}$
$\log F_X$ (0.3-5 keV)	$-12.53^{+0.02}_{-0.03}$	$-12.00^{+0.03}_{-0.03}$	$-12.51^{+0.03}_{-0.03}$	$-11.77^{+0.03}_{-0.04}$	$-12.48^{+0.03}_{-0.04}$	$-12.54^{+0.03}_{-0.04}$
$L_X(10^{35} \text{ erg cm}^{-2})$	$0.81^{+0.08}_{-0.07}$	$2.92^{+0.21}_{-0.20}$	$0.90^{+0.04}_{-0.04}$	$4.32^{+0.31}_{-0.38}$	$1.06^{+0.50}_{-0.48}$	$0.86^{+0.06}_{-0.08}$
cstat / d.o.f	$\frac{9990.35}{9357} \sim 1.07$	$\frac{9981.34}{9357} \sim 1.07$	$\frac{9994.98}{9358} \sim 1.07$	$\frac{9942.03}{9355} \sim 1.06$	$\frac{9970.34}{9356} \sim 1.07$	$\frac{9988.34}{9356} \sim 1.07$
$n_b (\text{cm}^{-3})$				-	-	-
$p (\text{cm}^{-3} \text{ K})$				-	-	-
Eth (erg)				-	-	-
Mb ($M_\odot$)				-	-	-

Stellar estimations: $L_x = (0.91-1.63) \cdot 10^{35} \text{ erg cm}^{-2}$, $E_i = (2.62 - 4.59) \cdot 10^{50} \text{ erg}$

N51E – Spectral fitting tree



SRG/eROSITA

- ❑ eROSITA: extended Roentgen Survey with an Imaging Telescope Array
- ❑ On-board the Russian-German “Spectrum-Roentgen-Gamma” mission
- ❑ Has done 4 all sky surveys and a 5th partially.
- ❑ 7 identical and co-aligned TM arranged hexagonally.
- ❑ Sharp and deep images over large sky areas (FOV $\sim 1^\circ$ diameter, avg resolution $\sim 26''$)
- ❑ Spectral information in the ~ 0.2 -10 keV range.



Illustration of SRG with eROSITA (left) and ART-XC, the russian X-ray telescope (right).

Credit: DLR