X-RAYING THE HOT PHASE OF THE LMC INTERSTELLAR MEDIUM

Pierre Maggi

CEA Saclay

The XMM-Newton LMC survey collaboration:
F. Haberl, P. Kavanagh, M. Sasaki, M. Filipović,
Y.-H. Chu, S. Snowden, S. D. Points, C. Maitra

and F. Acero & J. Ballet (CEA Saclay)

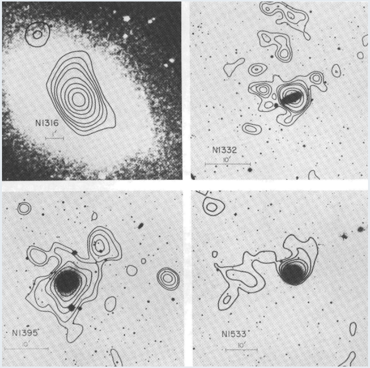
Interstellar Medium in the Nearby Universe, 26-28 March 2018, Bamberg

1. INTRODUCTION
2. THE MAGELLANIC CLOUDS IN X-RAYS
3. DATA ANALYSIS
4. RESULTS : PROPERTIES OF THE HOT GAS AND LINK WITH STAR FORMATION

The hottest component of the multi-phase ISM is a tenuous plasma ($\lesssim 1$ cm^{-3}) at high temperature of $\gtrsim 10^6$ K ($\gtrsim 0.1$ keV) $\mapsto$ This shines brightly in X-rays.

The largest component of the ISM *by volume*.

In both elliptical...



Einstein contours on *V* images (Forman+ 1985)

... and spiral galaxies

Chandra view of M83 (Long+ 2014)

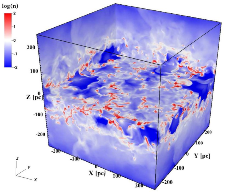
Origin of the hot interstellar medium

↦ Stellar feedback

- ▶ Winds from massive stars
- ▶ Shocks from supernova remnants

↦ AGN activity

▶ Relatively more important in elliptical galaxies ? (e.g. Diehl & Statler 2007, 2008)



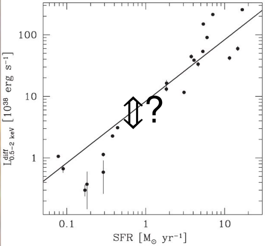
3D simulations of ISM including stellar feedback (Kim+2013)

The diffuse emission — star formation connection

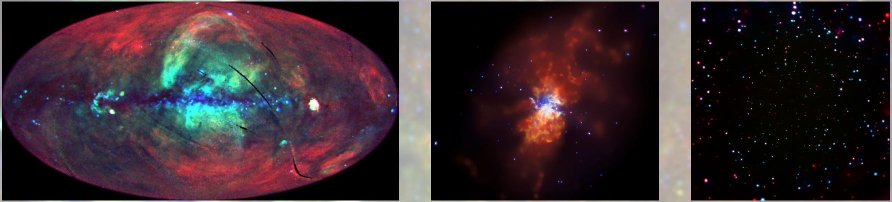
▶ Clear morphological similarities, in particular spiral arms (Strickland+2004)

↦ A *linear* Lx – SFR relation, but conflicting results for the coefficient [Strickland+04, Owen+09, Mineo+12]:

Can it be better calibrated ? Behaviour at low SFR ?



L_X – SFR relation for star forming galaxies (Mineo+2012)



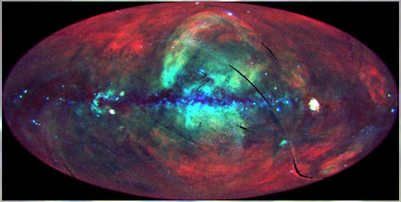
RASS (left), M82 in X-rays (middle), and Chandra Deep Field South (right)

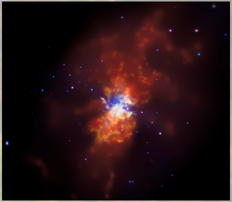
Issues in the Milky Way

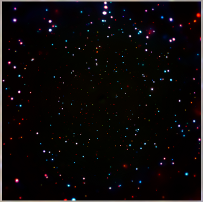
- Strong absorption
- Distance uncertainties
- line-of-sight confusion
- Need large scale coverage

Issues outside the Local Group

- Faint
- Spatial resolution (integrated study)
- Unresolved source contamination







RASS (left), M82 in X-rays (middle), and Chandra Deep Field South (right)

Issues in the Milky Way

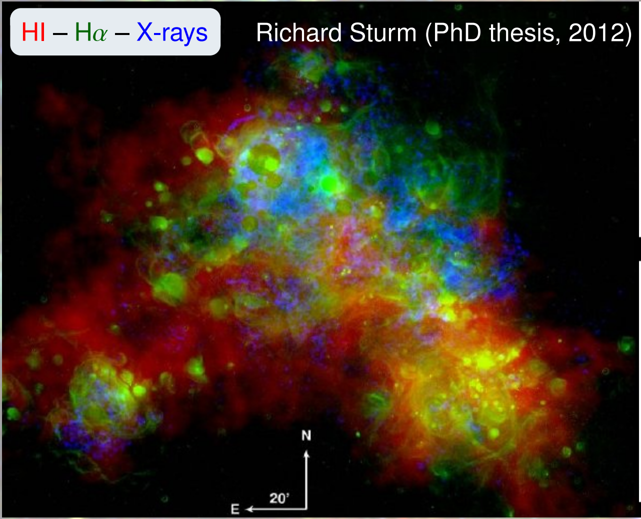
- Strong absorption
- Distance uncertainties
- line-of-sight confusion
- Need large scale coverage

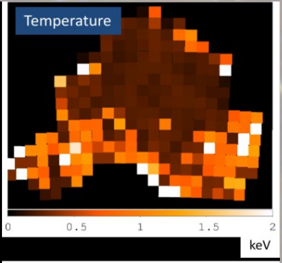
Issues outside the Local Group

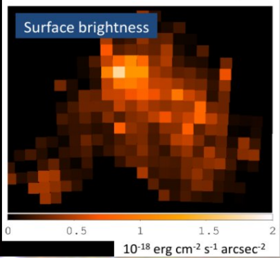
- Faint
- Spatial resolution (integrated study)
- Unresolved source contamination

The Magellanic Clouds

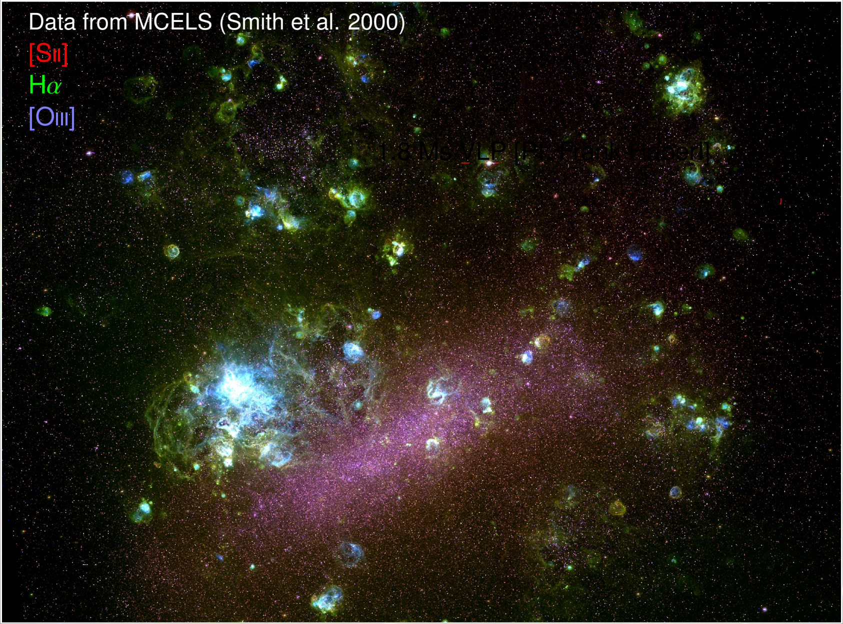
- Nearby (50 kpc and 62 kpc)
- High latitude / low absorption
- Well resolved with XMM (1' ~ 15 pc in LMC)
- Point source down to a few 10^{33} erg/s

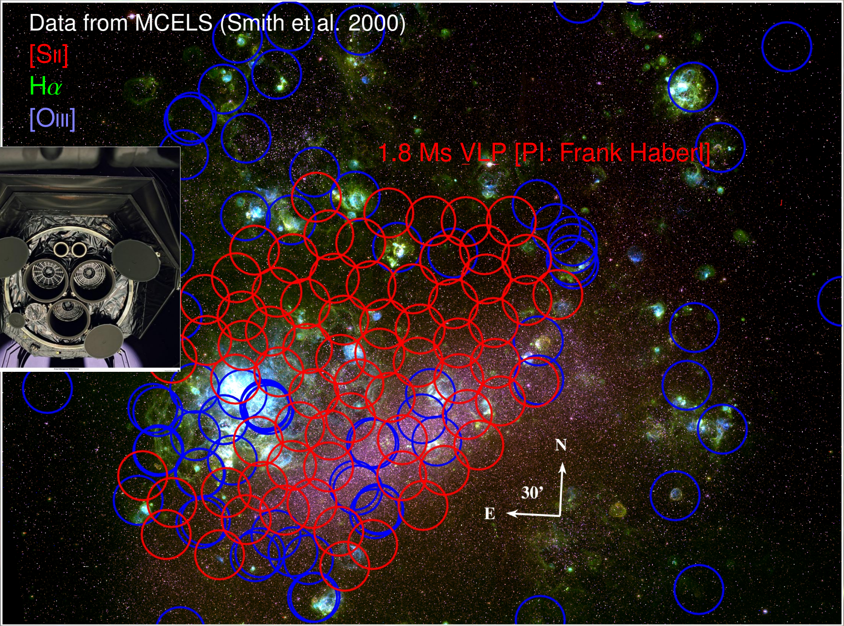






A rather constant temperature of 0.2 keV (2.3×10^6 K).
A total luminosity of 7×10^{36} erg/s (absorbed), or 4×10^{37} erg/s (unabsorbed).

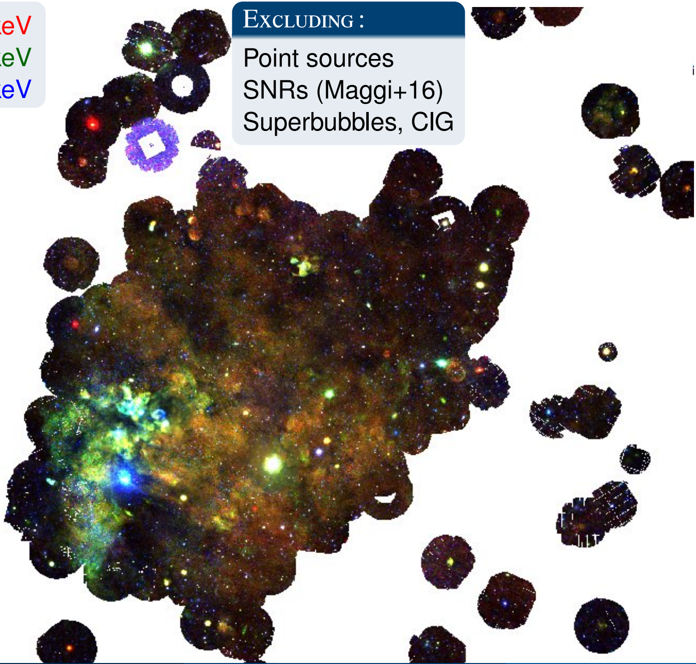

Data from MCELS (Smith et al. 2000)
[SII]
Hα
[OIII]
1.8 Ms VLP


Data from MCELS (Smith et al. 2000)
[SII]
Hα
[OIII]
1.8 Ms VLP [PI: Frank Haberl]
N
30'
E

0.3 – 0.7 keV
0.7 – 1.1 keV
1.1 – 4.2 keV

Excluding :

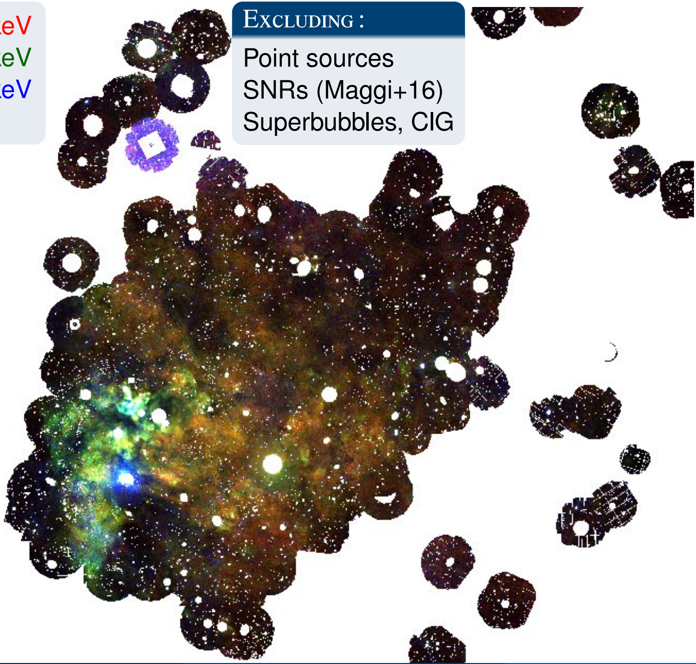
Point sources
SNRs (Maggi+16)
Superbubbles, CIG



0.3 – 0.7 keV
0.7 – 1.1 keV
1.1 – 4.2 keV
(blink me!)

Excluding :

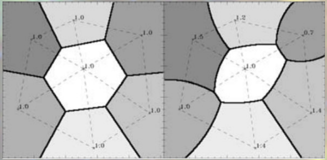
Point sources
SNRs (Maggi+16)
Superbubbles, CIG

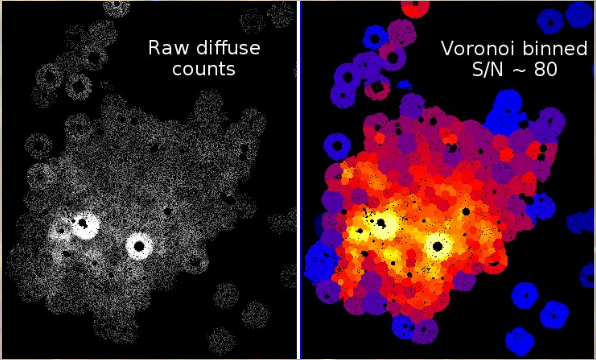


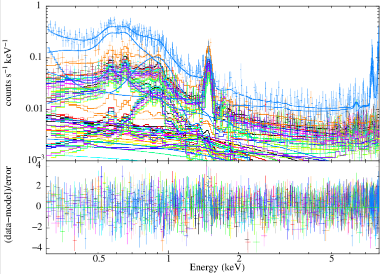
We would like a mapping of our mosaic to reach a constant S/N for spectral fitting :

Use a **weighted Voronoï Tesselation** (WVT) algorithm (Diehl & Statler 2006), on a count map of the diffuse emission (and associated variance):

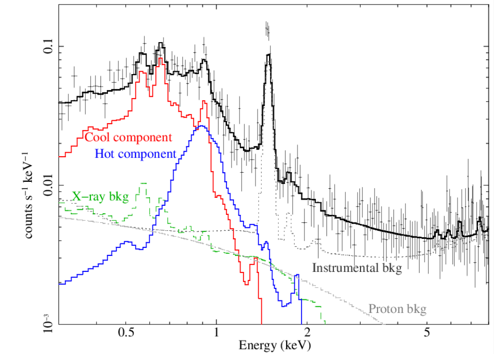
Diffuse counts = Observed counts - Out-of-time - Background (X-ray/instrumental)







Simultaneous fitting (up to 62 spectra !)



Two-temperature fitting (only one spectrum shown)

Physical parameters

- Temperatures
- Emission measure : EM = $\int n_e n_H dV$
- Abundances of main elements (O, Ne, Mg, Fe)

Other parameters

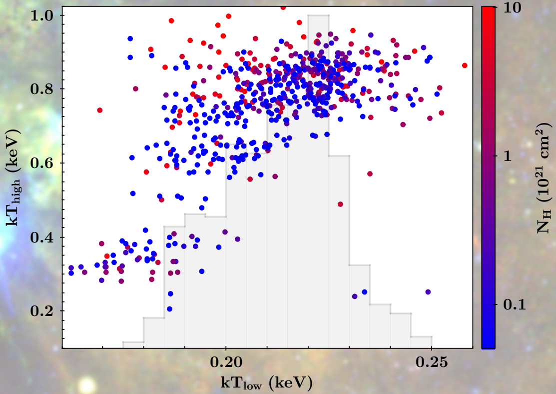
- N_H column (***up*** to the gas)
- Surface brightness of the hot gas

1 Introduction

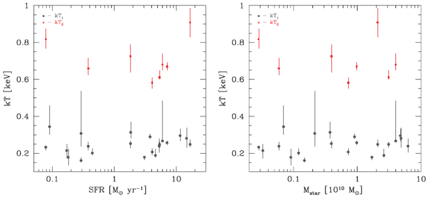
2 The Magellanic Clouds in X-rays

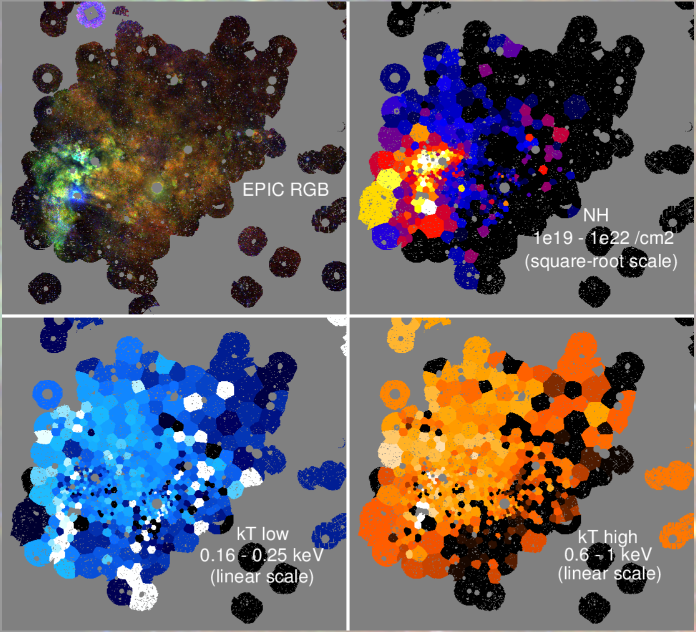
3 Data analysis

4 Results : Properties of the hot gas and link with star formation
- Temperature distribution
- Parameter maps
- X-ray vs. SFR



Same range of temperature as in external galaxies (e.g. Mineo+12)

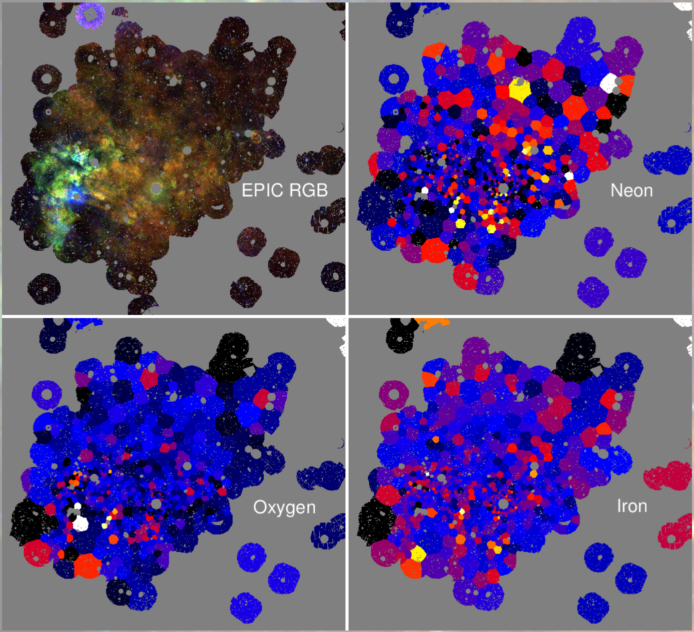




S/N of 80

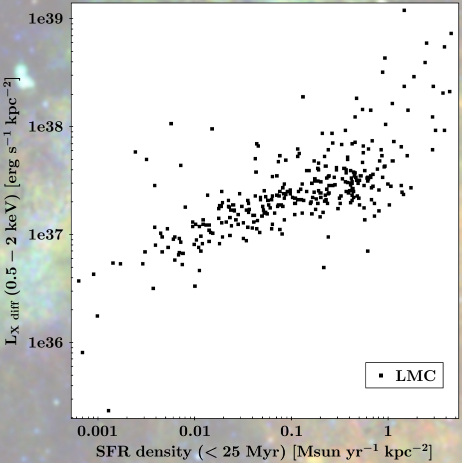
$\sim$ 50 arcmin^2
(median)

2-*kT* model with
free abundances



No strong variation (point-to-point)

Uniform when averaged over large regions

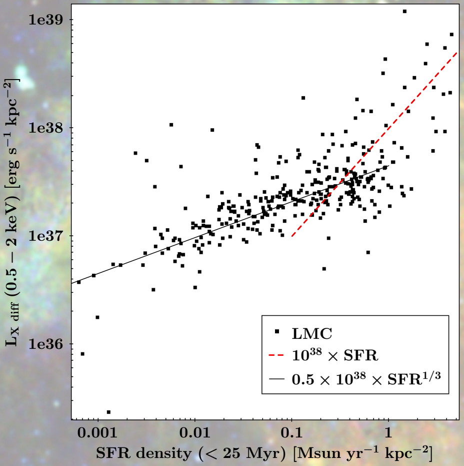


(SFR taken from Harris & Zaritsky 2009.)

Luminosities corrected for absorption

$\gtrsim$ 100 regions with consistent analysis.
SFR spans several orders of magnitude.

Less than linear correlation



(SFR taken from Harris & Zaritsky 2009.)

Luminosities corrected for absorption

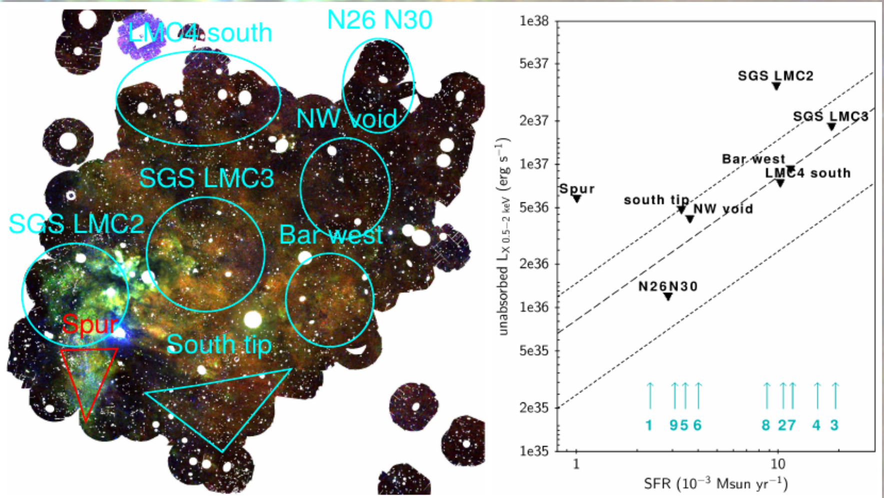
$\gtrsim$ 100 regions with consistent analysis. SFR spans several orders of magnitude.

Less than linear correlation

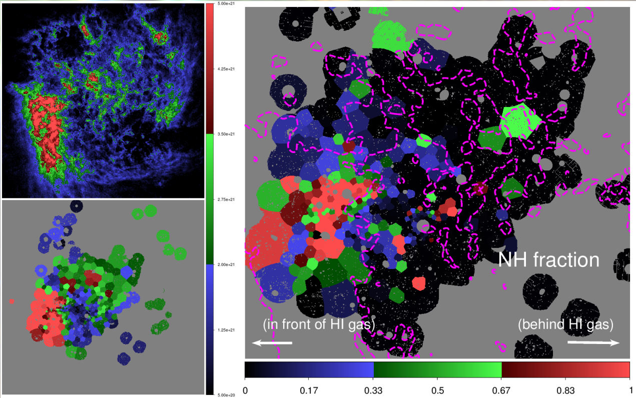
Lower $L_{X\ \mathrm{diff}}/SFR$ than for spiral galaxies (with higher SFRs) :

- Lower metallicity ?
- Hot gas escape ?

$L_X^{\rm diff}$ vs. SFR (<25 Myr) integrated over regions with different star formation histories (Harris & Zaritsky 2009) and supergiant shells (SGS, Meaburn 1980). Dashed and dotted lines are $L_X^{\rm diff}$/SFR relations from the literature. ↦ OK within scatter, and south-east outliers.



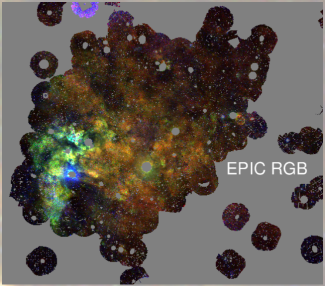
Left : Total N_H column density (top, Kim+2003), averaged over the Voronoï bins (bottom).
Right : **“N_H fraction”:** $N_H^X / N_H^{21\,\mathrm{cm}}$ gives the line-of-sight position relative to the main gas disk

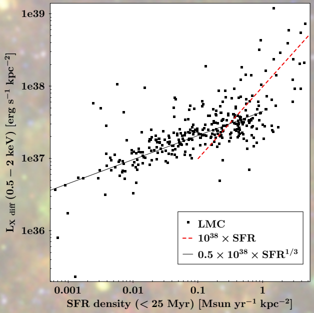


In front of the gas disk in the vast north-west region ↦ signs of outflow ?

X-ray diffuse emission of the LMC ISM

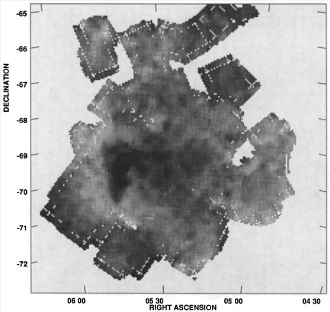
- Combining hundreds of exposures
- Homogeneous coverage of the central area
- Extensive spectral analysis
  - Parameter maps at ≈100 pc scale
  - Uniform abundances in gas phase
- Probing the $L_X^{\rm diff}$/SFR relations down to unprecedented low SFR regime
- Sub-linear relation
  - Outflows ?
- Multi-wavelength imaging
  - Radio
  - Far/Mid Infrared
  - Gamma rays

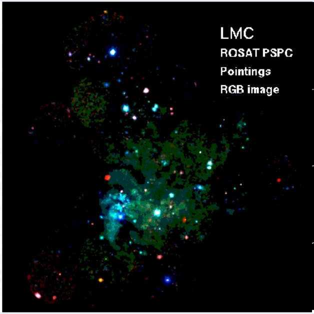


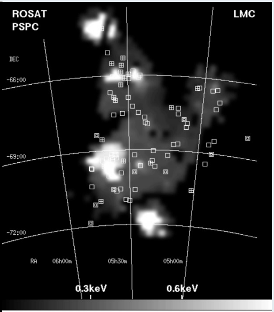


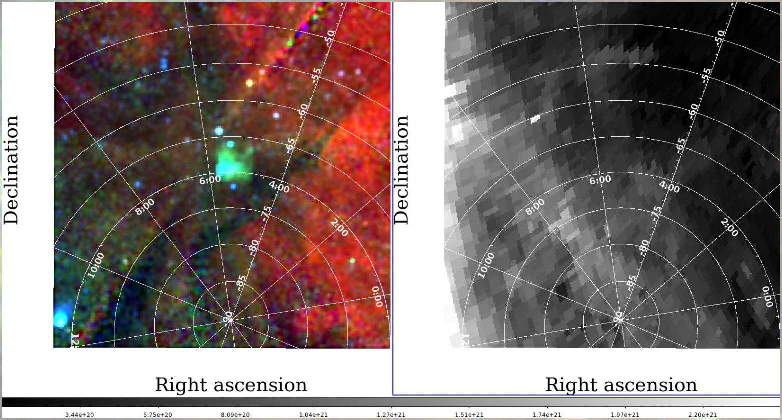
Thank you for your attention

- Already “imaged” with *Einstein*/IPC (left, Wang+1991),
  - ↪ Two main temperature components in integrated spectrum.
- Clearly seen in pointed ROSAT PSPC survey (centre, Haberl+1999)
- Temperature map (right) from Sasaki+2002 (1-kT fit).





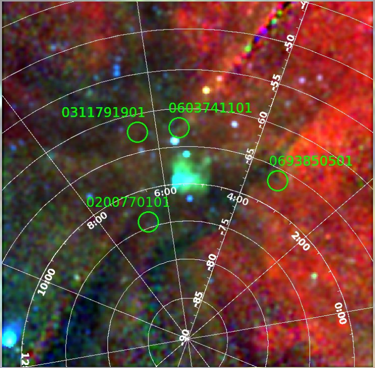


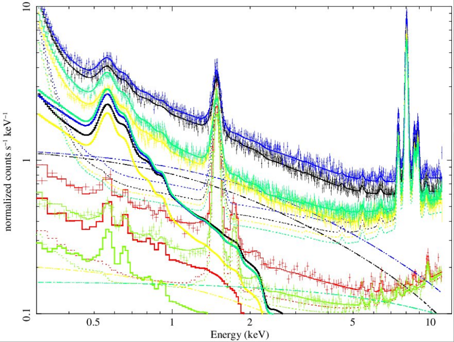


RASS maps (0.1-2.4 keV) and Galactic N_H in a 50° box around the LMC.

MISSING INGREDIENTS:

- Knowledge of the AXB spectrum
- Dealing with RASS artefacts.

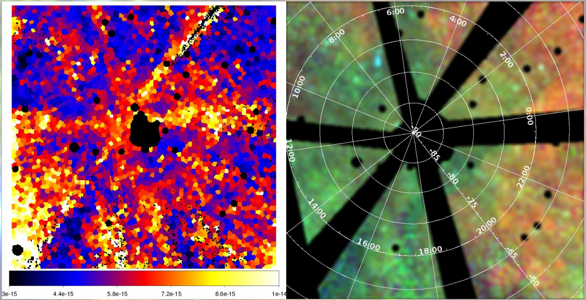




Param	Value
kT_1	57 ± 3 eV
kT_2	121^{+15}_{-10} eV
kT_3	224 ± 5 eV
CXB	4.4×10^{-4} ph cm^{-2} s^{-1}

AXB SURFACE BRIGHTNESS:

$$SB_{AXB}(0.3 - 10\mathrm{keV}) = R_{45\ RASS} \times m_i\,(N_{H\ \mathrm{Gal}})$$

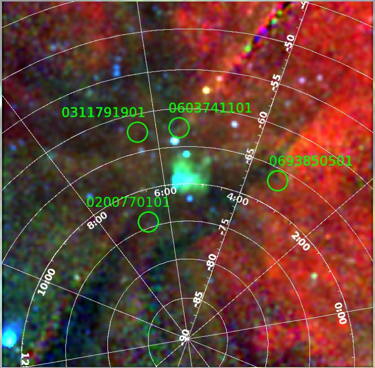


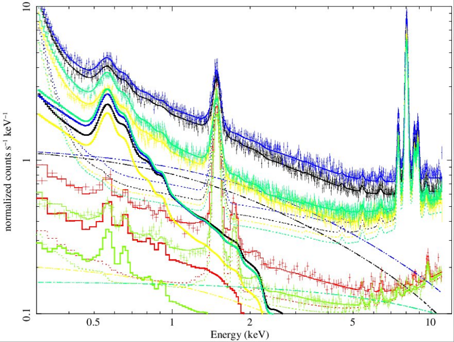
Left: AXB surface brightness map (0.3-10 keV), in units of $\mathrm{erg\,cm^{-2}\,s^{-1}\,arcmin^{-2}}$.
Right: Masked point sources, LMC, Galactic plane ($|b| < 10°$), and “LTE strip”.

The AXB in LMC is flat at a few %:

$$SB_{AXB}(0.3 - 10\mathrm{keV}) = 9.6(^{+1.2}_{-1.7}) \times 10^{-15}\ \mathrm{erg\,cm^{-2}\,s^{-1}\,arcmin^{-2}}\ (\text{median}\ (^{Q90}_{Q10})).$$

Include the AXB model XSPEC *atable*, taking as parameters the size in arcmin^2 of the spectrun, $N_{H\ \mathrm{gal}}$, and $N_{H\ \mathrm{LMC}}$. One constant to account for 20 % scatter
$\mapsto$ **This adds only one free parameter per *observation*.**





AXB Surface Brightness:

$SB_{AXB}(0.3 - 10\mathrm{keV}) = R_{45\ RASS} \times m_i\left(N_{H\ \mathrm{Gal}}\right)$

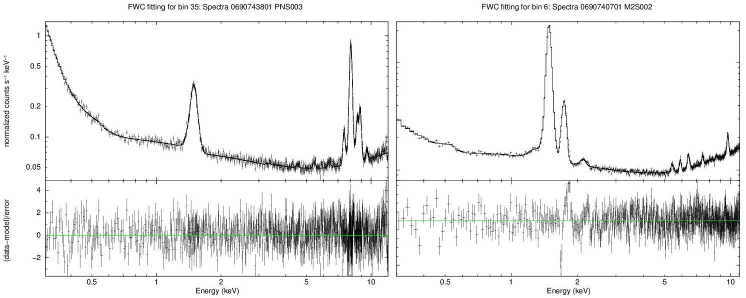
The AXB in LMC is flat at a few %:

$SB_{AXB}(0.3 - 10\mathrm{keV}) = 9.6(^{+1.2}_{-1.7}) \times 10^{-15}$ erg cm^{-2} s^{-1} arcmin^{-2} (median $(^{Q90}_{Q10})$).

Extraction area of the spectrun, $N_{H\ \mathrm{gal}}$, and $N_{H\ \mathrm{LMC}}$ *fixed*.

$\mapsto$ **This adds only one free parameter per *observation*.**

- Use the Filter Wheel Closed data available through XMM-Newton SOC.
- Cast the events of each pointings using attitude file, making sure to obtain spectrum from same detector position.
- Use phenomenological models (PN: Sturm 2012, MOS: Maggi+2016)



After fitting each spectra, we can include the best-fit results in our background model, only allowing a free renormalisation parameter

$\mapsto$ **This adds one free parameters per *spectrum*.**

A second instrumental background component, soft proton contamination (SPC) is a *flaring* component. We can identify it in two ways:

i) Ratio of high energy count rates in the FWC data (QPB + no protons) to that in the (point source filtered) SOURCE data (QPB + protons)
ii) Using (a variation of) the Fin/Fout ratio script of Molendi+2014, available through XMM SOC.

- We filter out the most affected exposures (about 10 %).
- In the other, we add a background component following prescription of Kuntz and Snowden 2008 (not convolved with RMF).

$\mapsto$ **This adds two free parameters per *spectrum*.**

We would like a mapping of our mosaic to reach a constant S/N for spectral fitting:

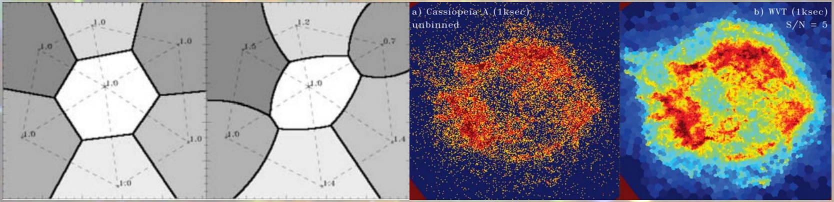
i) Get count maps of the diffuse emission and associated variance:

$C^{k,i}_{\text{diff}} = \left[C^{k,i}_{\text{observed}} - f_{OoT} C^{k}_{OoT} - C^{k,i}_{FWC} - C^{k,i}_{XRB}\right] \times \text{Mask}^i$ for instrument k, band i

$\left(\Delta C^{k,i}_{\text{diff}}\right)^2 = \left[C^{k,i}_{\text{observed}} + f_{OoT} C^{k}_{OoT} + C^{k,i}_{FWC} + \sigma^2_{XRB} C^{k,i}_{XRB}\right] \times \text{Mask}^i$

$C^{k,i}_{XRB}$ is the count rate of our AXB model (for any EPIC instrument) in band i, multiplied by the corresponding exposure map.

ii) Use a weighted Voronoï Tesselation (WVT) algorithm (Diehl & Statler 2006).



Use various S/N thresholds: low for imaging, medium for simple fitting, high for detailed spectral results (e.g. abundances).