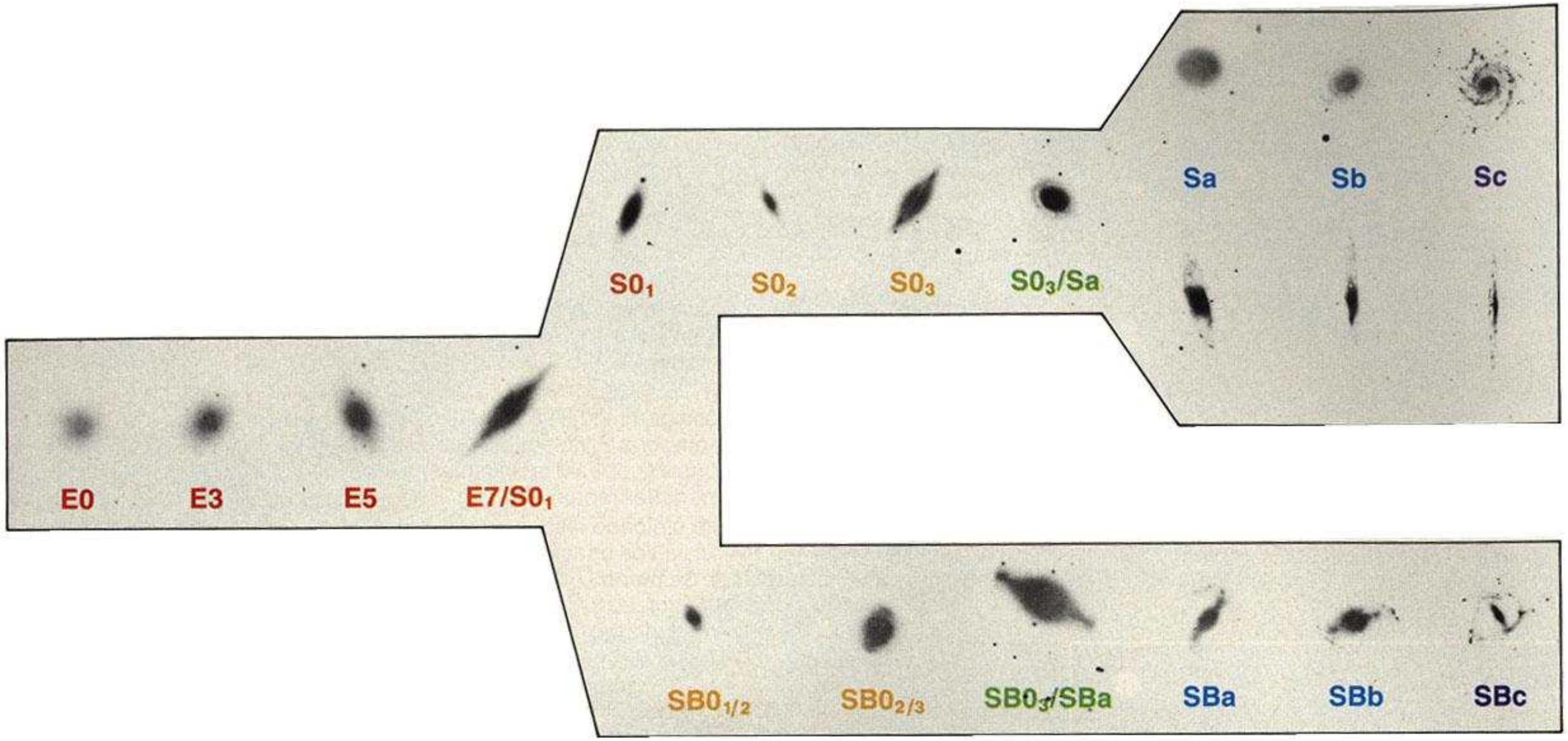
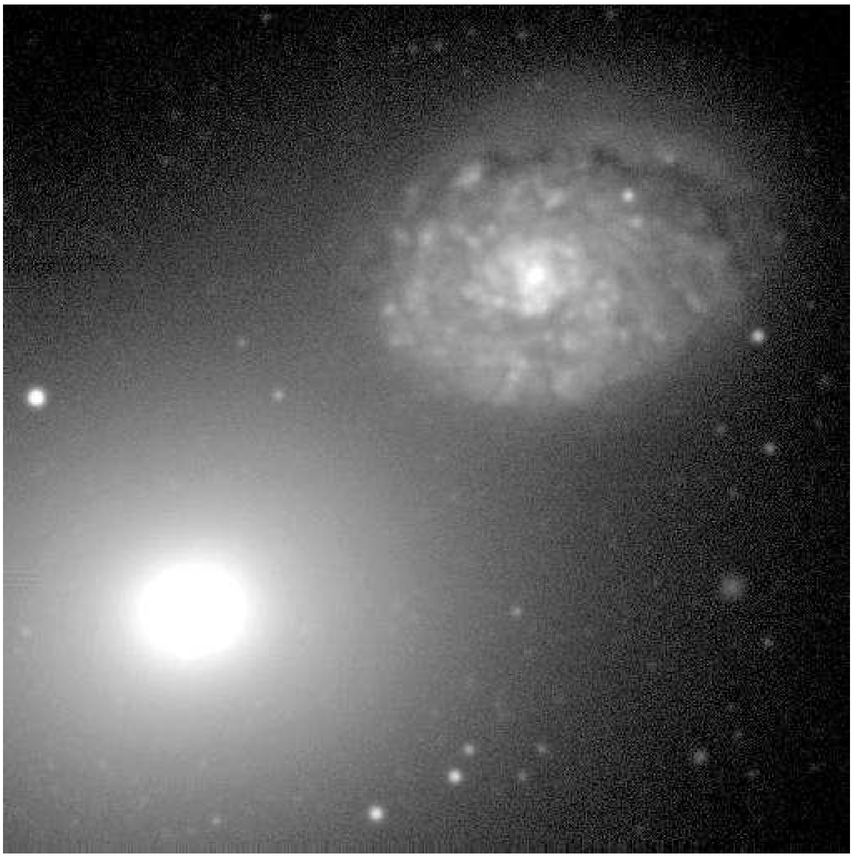
X-Rays from Normal Galaxies

Galaxy Classification

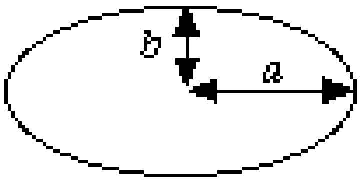


Galaxy classification via the Hubble “tuning fork diagram” courtesy George Lake, U. of Washington.

Elliptical Galaxies



M60 (NGC 4649), E1, U. of Alabama



Elliptical galaxies: Classification as Ex where $x = 10(a - b)/a$ (integer part; between 0 and 7); galaxies are low on dust and gas, red color ($B - V \sim 0.9$), typically low luminosity and low mass ($10^6\,M_\odot$)

Monsters: Also elliptical, from mergers in galaxy clusters (e.g., M87 in Virgo), M up to $10^{12}\,M_\odot$, designated cD.

Spiral Galaxies

M51 (NGC 5194 and 5195), Sc and Irr, Kitt Peak 0.9 m

Spiral Galaxies: Elliptical nucleus plus spiral arms, designated Sa, Sb, Sc depending on opening angle of spiral (Sa: $\sim 10^\circ$, Sc: $\sim 20^\circ$) and dominance of nucleus.

Bluer than ellipticals ($B - V \sim 0.8$)

Mass content $\sim 3 \times 10^{11} M_\odot$, with $M/L \sim 20$,

Gas content increases from Sa to Sc from 1% to 8%.

Spiral arms probably due to density wave.

Barred Galaxies

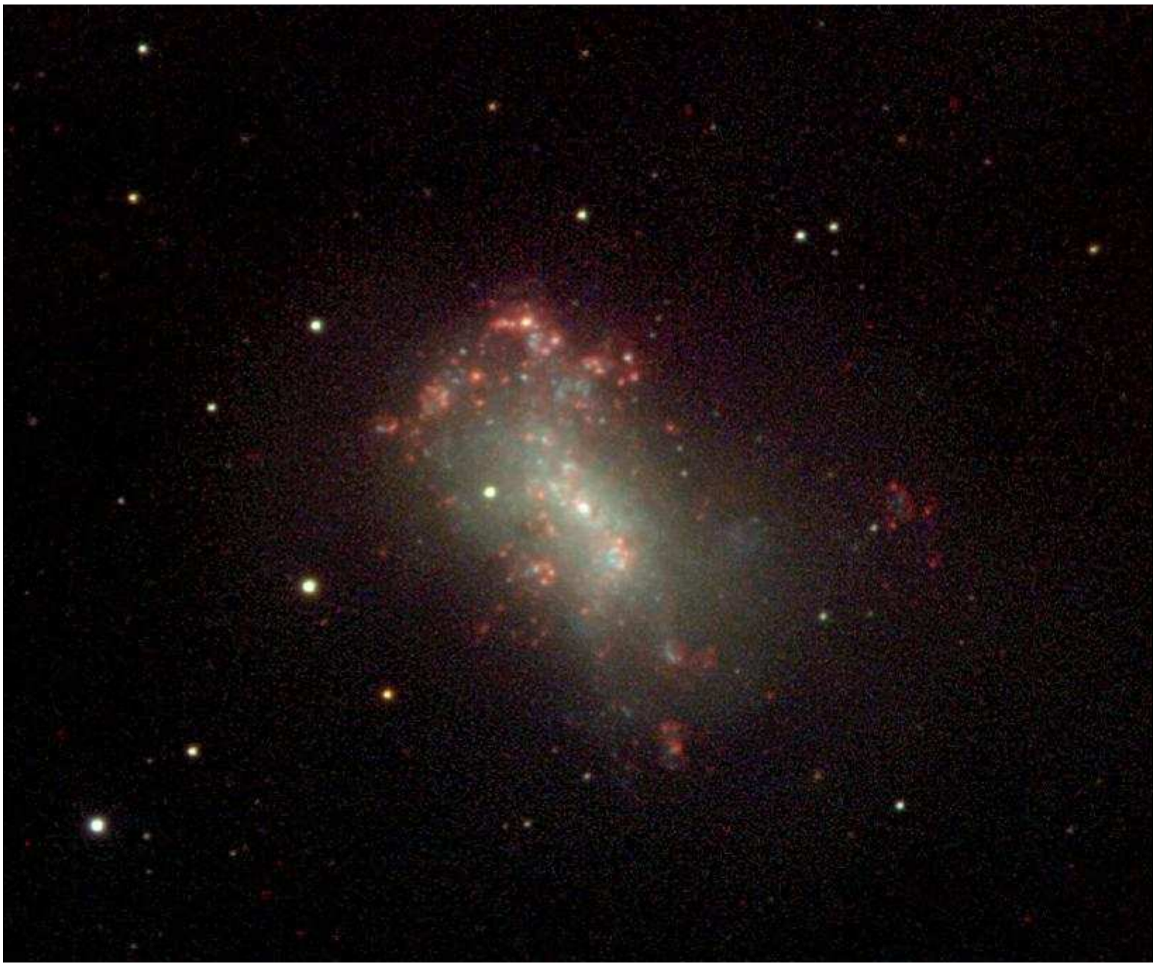
M95 (NGC 3351), SBb, INT

Barred Galaxies: Classifi cation as SBa, SBb, SBc similar to Sx galaxies, but additional presence of a bar (cause of bar production and stability are still debated).

Similar masses and gas content as in normal spirals.

Milky Way is a barred spiral.

Irregular Galaxies, I

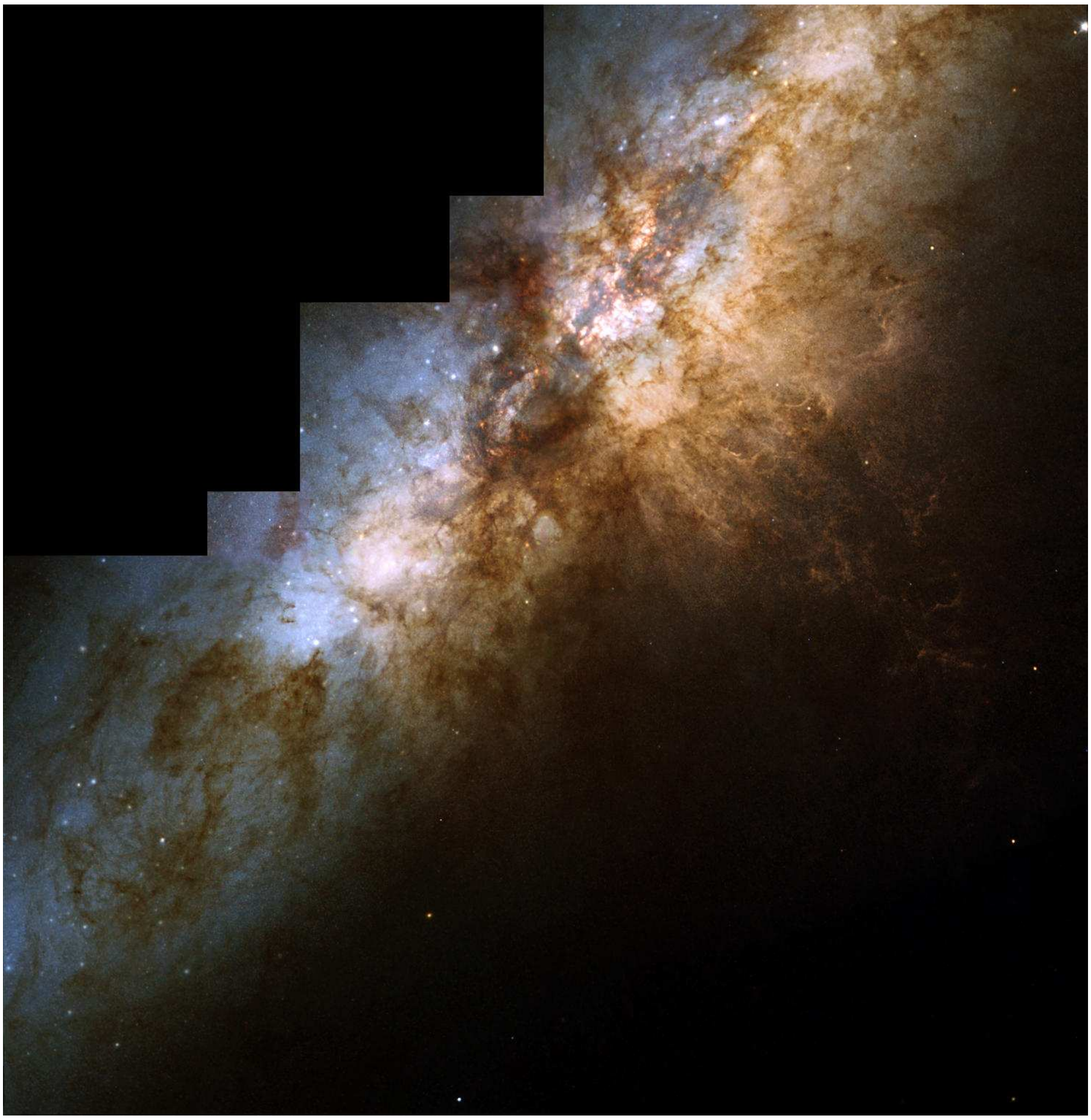


NGC 4449, Univ. Bonn

Irr I: no symmetry or spiral arms, bright knots of O- and B-type stars, very blue ($B - V \sim 0.5$), high dust content ($\sim$ 16%), $M/L \sim 3$, masses vary appreciably from 10^6 to $10^{10}\,M_\odot$.

Examples: SMC, LMC $\Longrightarrow$ "Magellanic type irregulars".

Irregular Galaxies, II



M82, HST-WFPC

Irr II: unsymmetrical and "abnormal"

$\Longrightarrow$ All objects that do not fi t in the rest of the classifi cation: starburst galaxies, interacting galaxies, AGN,. . .

X-Ray Emitting Objects

All objects spoken about so far in this class are members of the milky way $\Longrightarrow$ X-ray emissivity of the galaxy as a whole is sum over X-ray emitting objects.

Therefore, X-ray emissivity is dominated by point sources:

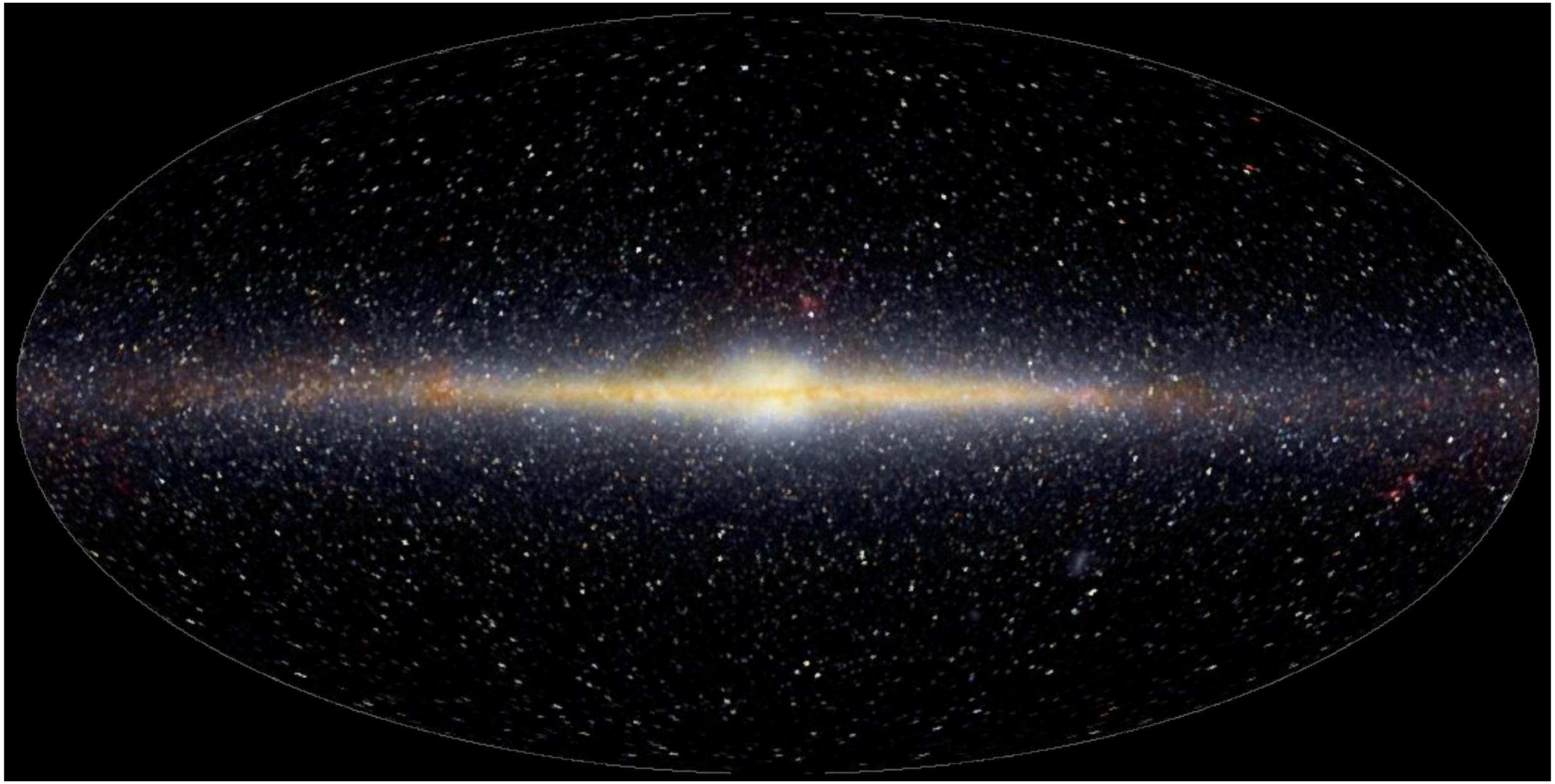
- Stars
- Supernova Remnants
- Low Mass X-Ray Binaries
- High Mass X-Ray Binaries

and by continuum sources

- Nuclear Decay

On the next few slides we will look at some examples.

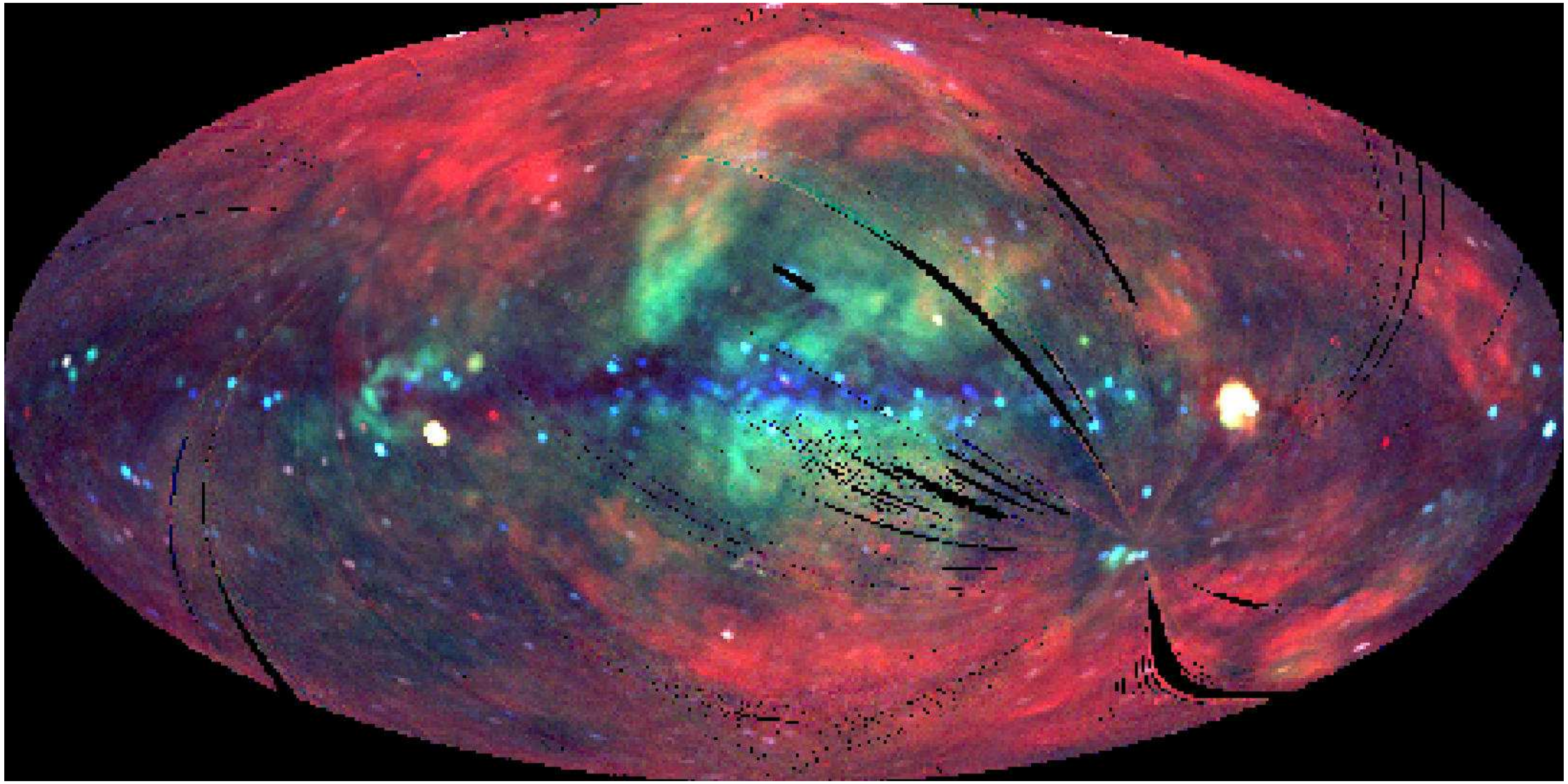
Milky Way: Overview



COBE image (IR): white: stars, red: dust

image in galactic coordinates.

Milky Way: Overview



Low latitudes dominated by stellar X-ray sources, high latitudes by hard extragalactic sources.

Milky Way: Overview

At higher energies: emission lines from radioactive nuclei

Review: Diehl & Timmes, 1998, PASP, 110, 637

short lived nuclei: evidence of *in situ* nucleosynthesis. Best example: ^{26}Al.

Produced by proton capture reactions, mainly ^{25}Mg, in

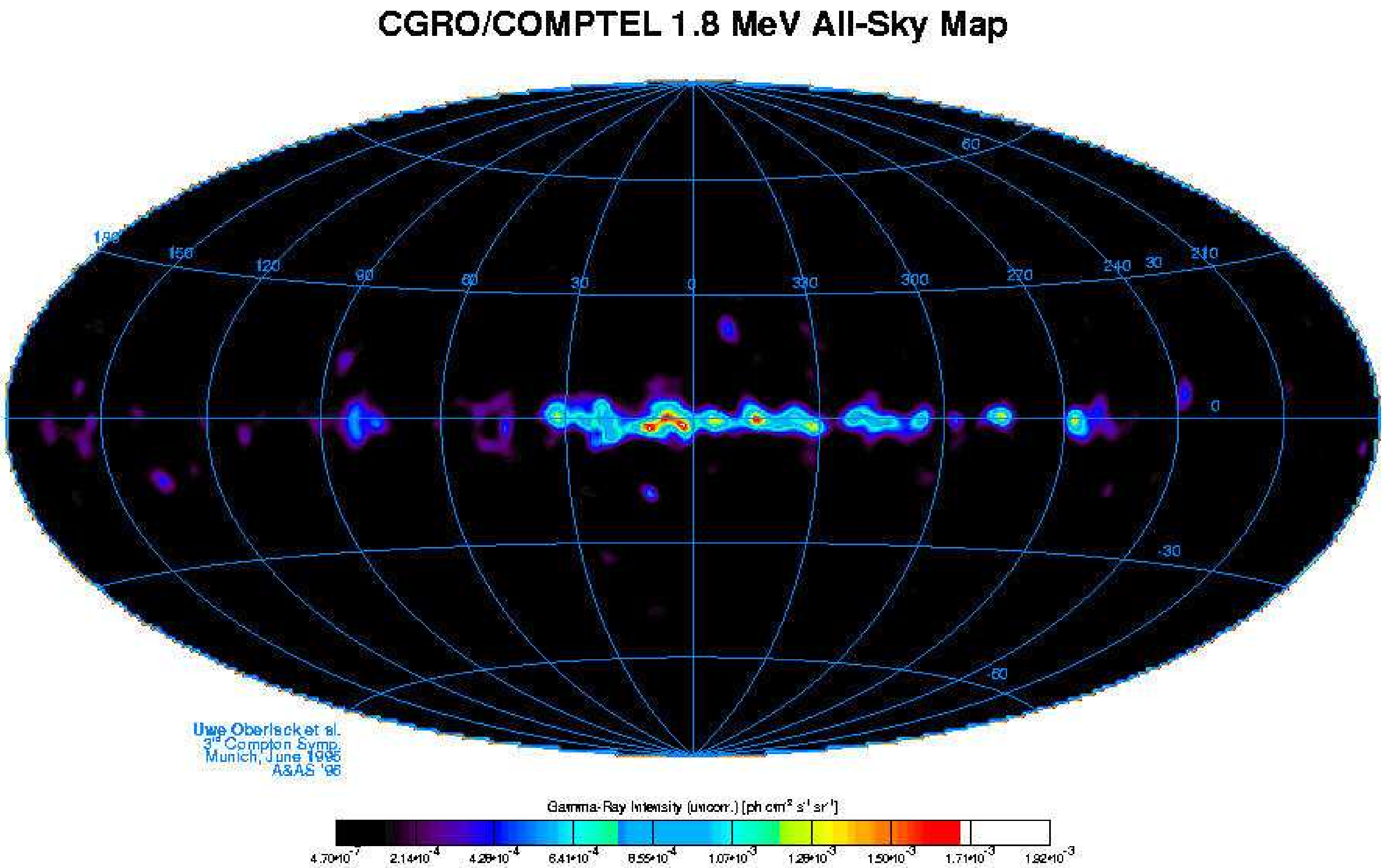
- hydrogen burning in massive stars ($M > 11\,M_\odot$)
- shell burning on the AGB
- explosive H burning in novae

and ejected with stellar wind.

^{26}Al traces massive stars.

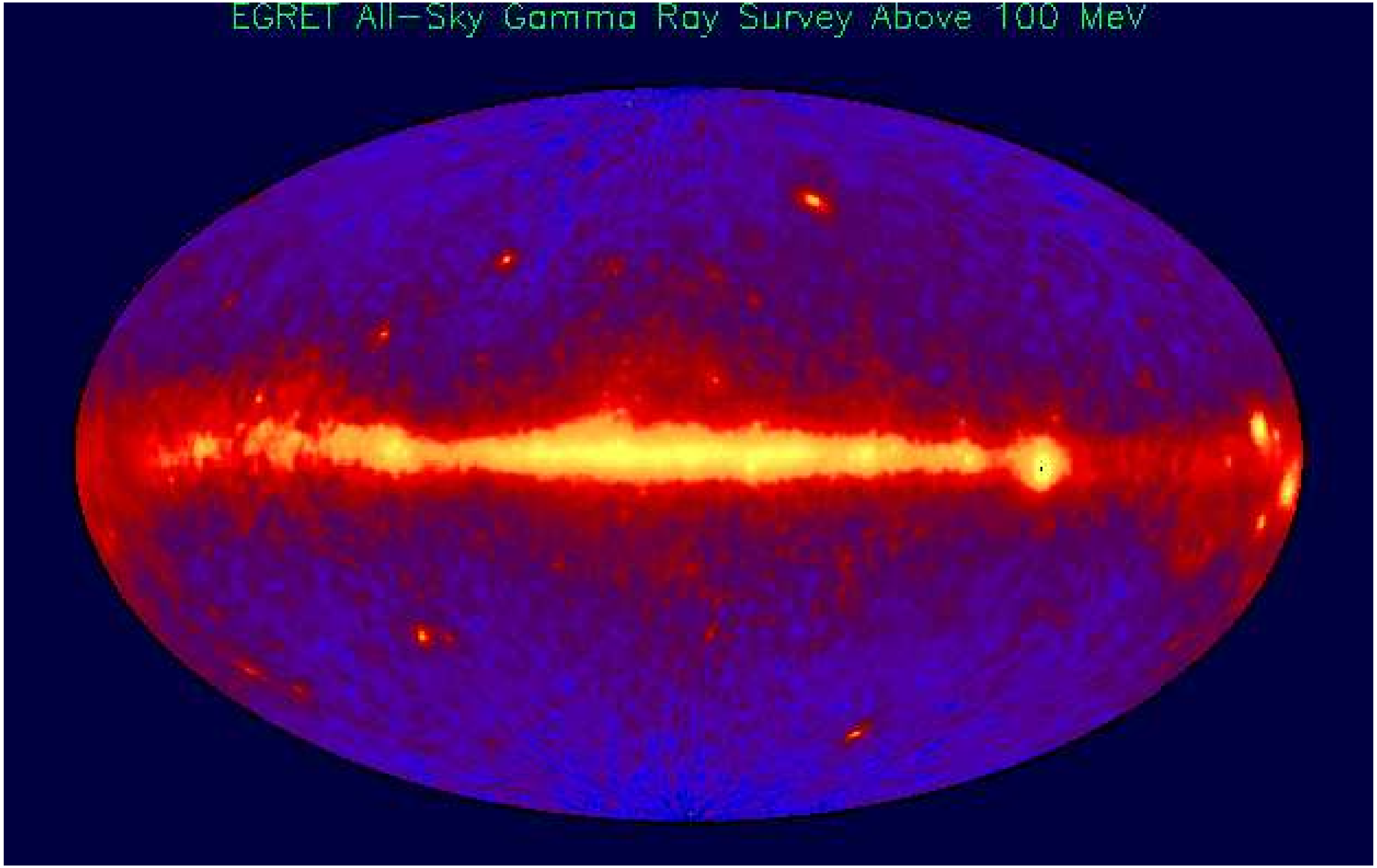
Detection: decays with half life of 7.5×10^5 yr into ^{26}Mg, emitting 1.809 MeV gamma-rays.

Milky Way: Overview



Distribution of ^{26}Al emission from CGRO/COMPTEL; concentrated on starbirth regions.

Milky Way: Overview



At even higher energies (CGRO/EGRET): emission due to the interaction of cosmic rays with the ISM. For details see class on "Cosmic Rays".

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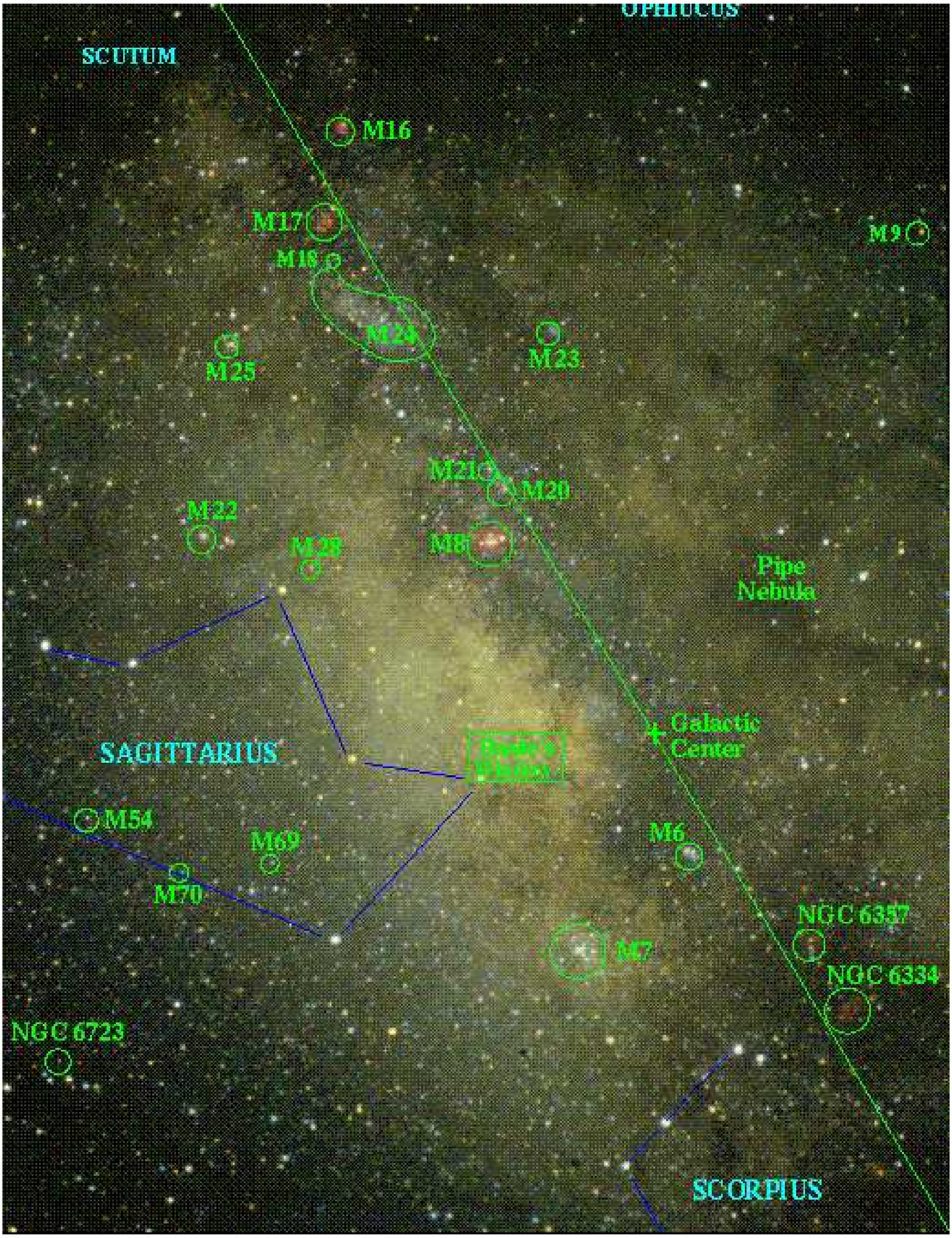
Galactic Center, I

$d = 8.5\,\mathrm{kpc} \Longrightarrow 1^\circ \sim 140\,\mathrm{pc}$, $1' \sim 2\,\mathrm{pc}$

Galactic Center, II



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Galactic Center, III

Within 300 pc around galactic center: $10^8\,M_\odot$ of molecular gas $\Longrightarrow \sim 5\%$ of total molecular gas in galaxy, concentrated in 0.04% of surface area.

Major problem: very large extinction ($A_\mathrm{V} \sim 30$) towards galactic center $\Longrightarrow$ Optical Astronomy impossible.

Solution: At longer λ, grains are transparent $\Longrightarrow$ Infrared, radio, and X-ray observations!

Galactic Center, IV

2MASS image (Infrared), color coded, $2^\circ \times 2^\circ$

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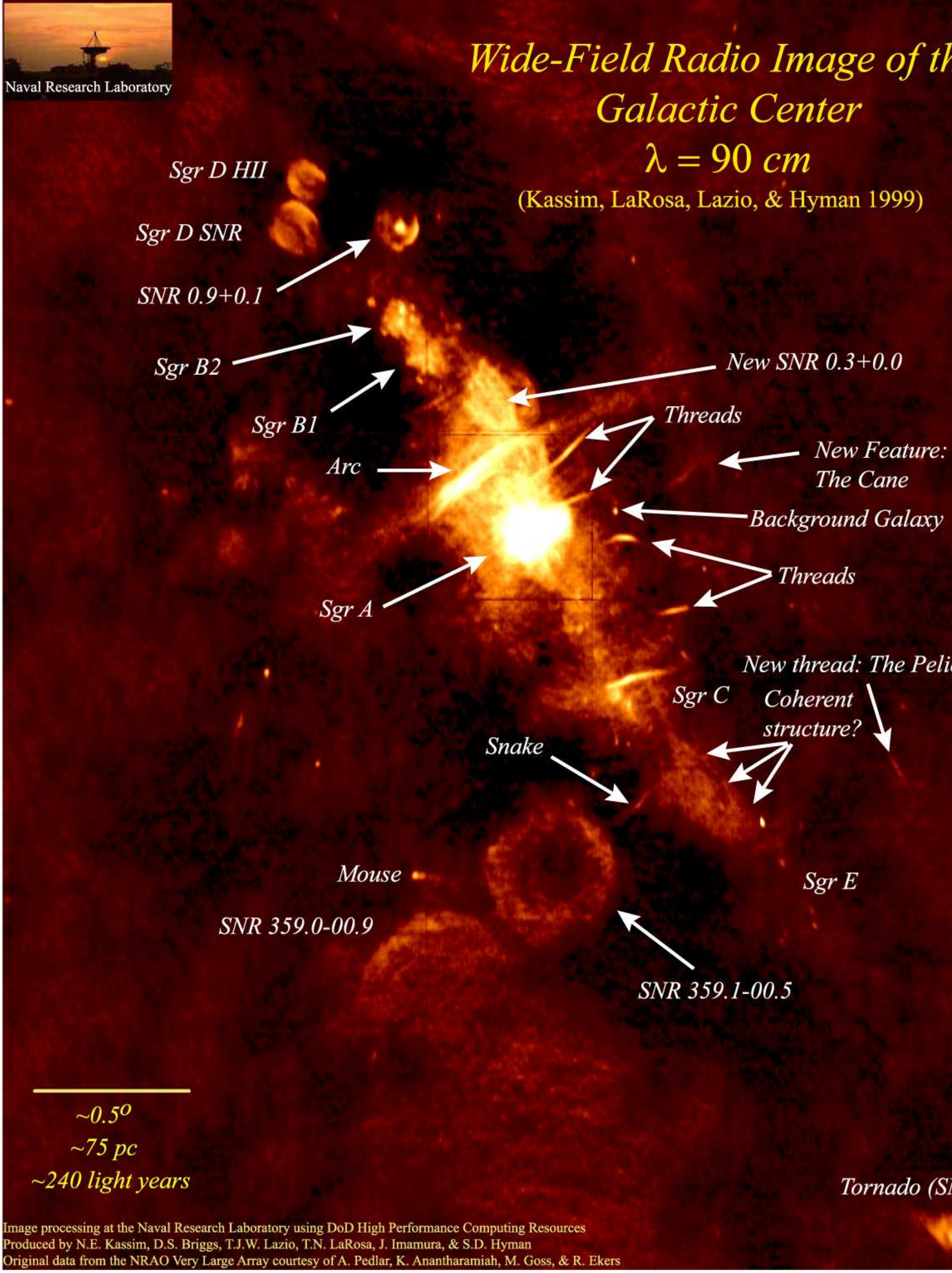
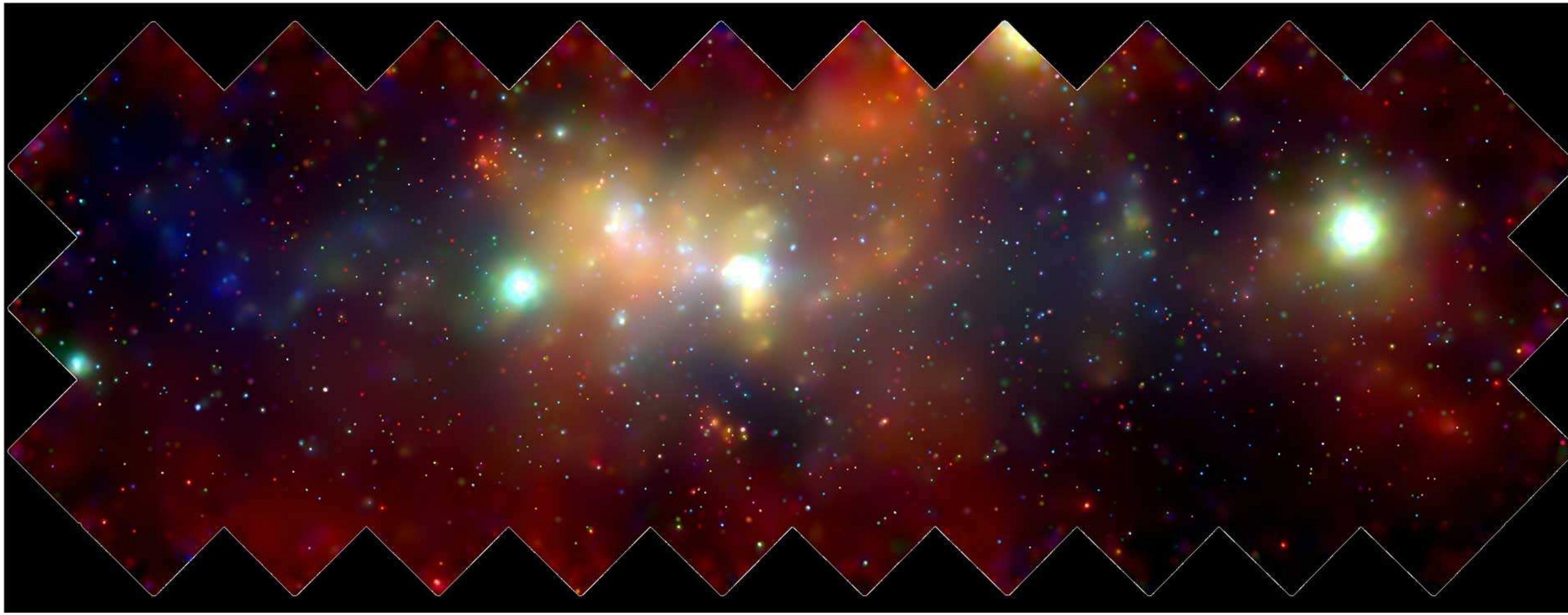
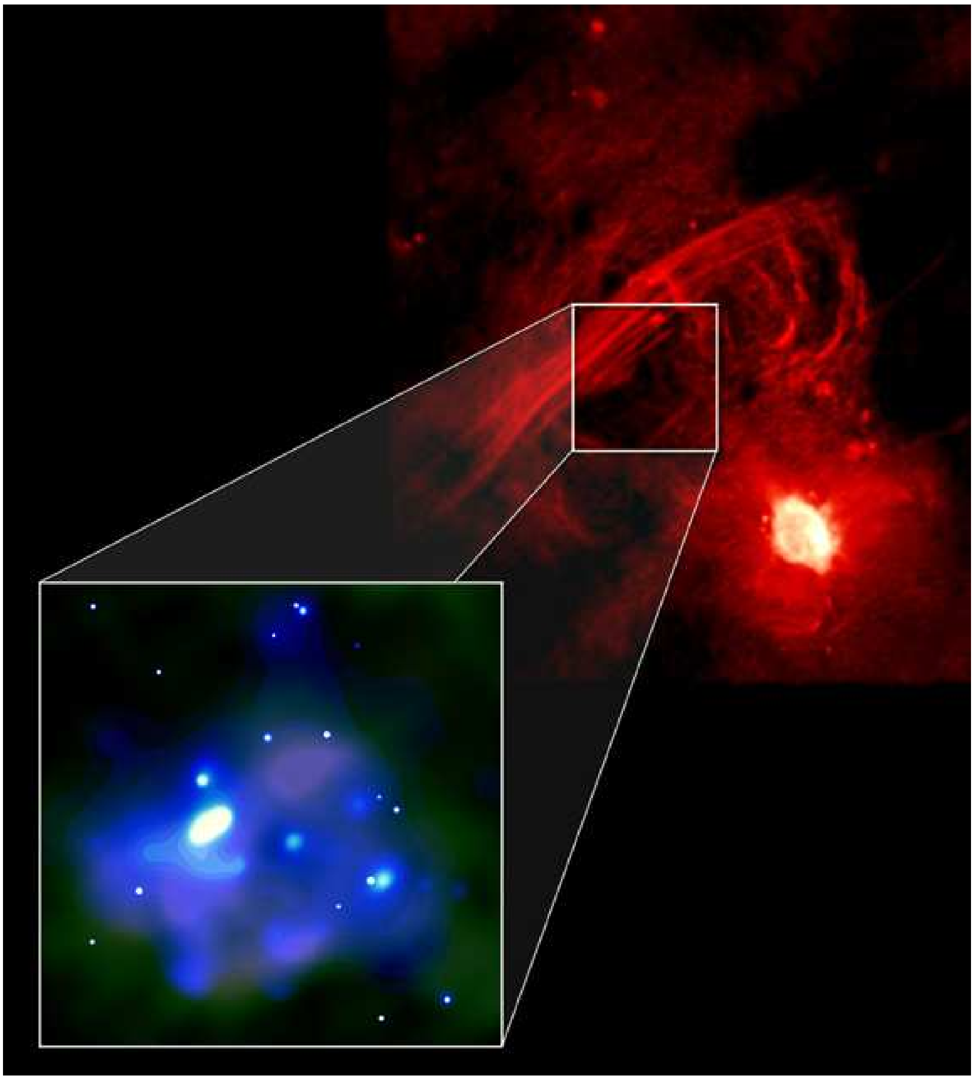

Naval Research Laboratory
Wide-Field Radio Image of th
Galactic Center
λ = 90 cm
(Kassim, LaRosa, Lazio, & Hyman 1999)
Sgr D HII
Sgr D SNR
SNR 0.9+0.1
Sgr B2
Sgr B1
New SNR 0.3+0.0
Threads
New Feature:
The Cane
Arc
Background Galaxy
Threads
Sgr A
New thread: The Peli
Sgr C
Coherent
structure?
Snake
Mouse
Sgr E
SNR 359.0-00.9
SNR 359.1-00.5
~0.5°
~75 pc
~240 light years
Tornado (S
Image processing at the Naval Research Laboratory using DoD High Performance Computing Resources
Produced by N.E. Kassim, D.S. Briggs, T.J.W. Lazio, T.N. LaRosa, J. Imamura, & S.D. Hyman
Original data from the NRAO Very Large Array courtesy of A. Pedlar, K. Anantharamiah, M. Goss, & R. Ekers



Chandra mosaic of innermost 400×900 ly region around galactic center. Diffuse radiation plus many individual sources (responsible for most of observed Fe Kα emission earlier thought to be due to diffuse gas); diffuse gas temp $\sim 10^7$ K.

Sgr A and the Arc



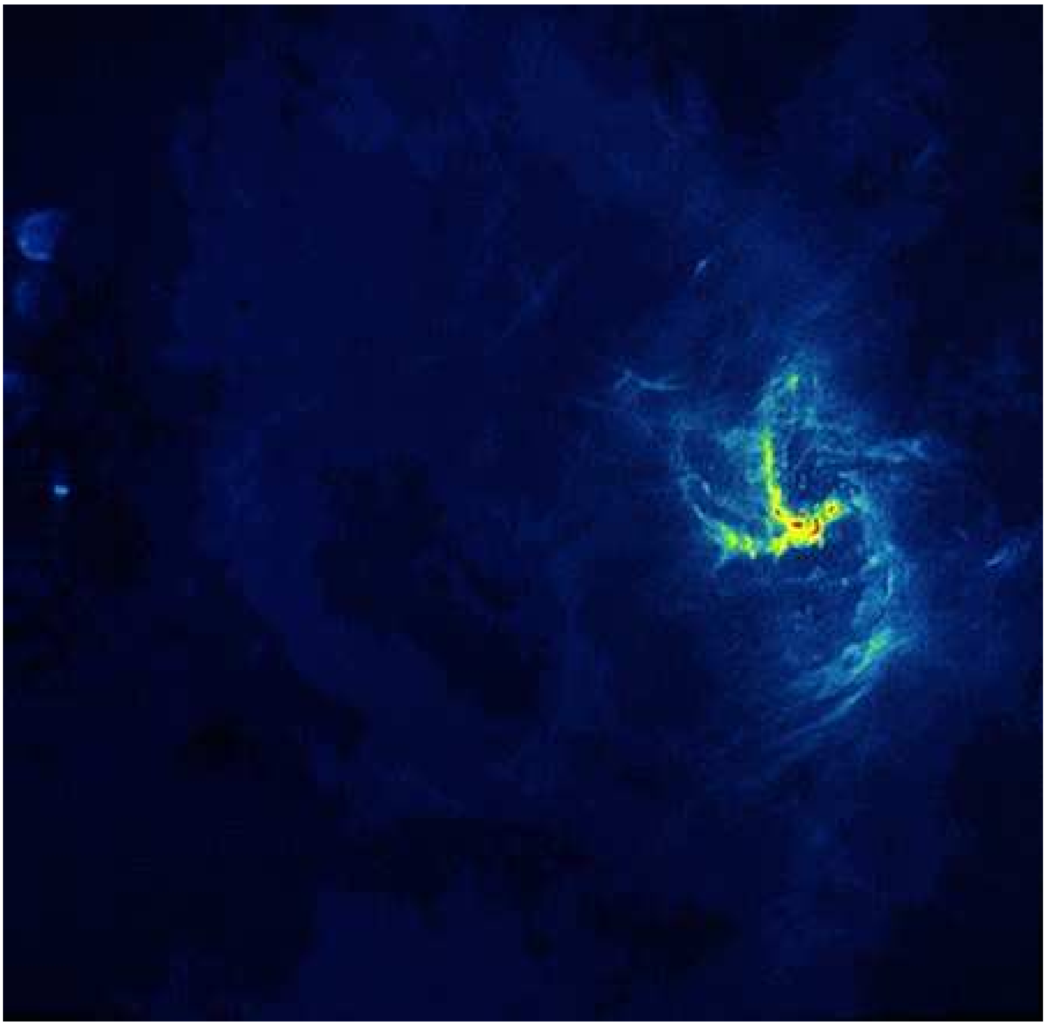
courtesy F. Yusef-Zadeh; Chandra (blue) / mm (green): $8' \times 7'$, radio: $30' \times 30'$

Arc: $5''$ (=0.2 pc) wide radio filaments, part of much larger Ω shaped structure $\perp$ galactic plane. Polarized and steep radio spectrum $\Longrightarrow$ Synchrotron radiation!

$8'$ (24 pc) diam. radio halo surrounding Sgr A

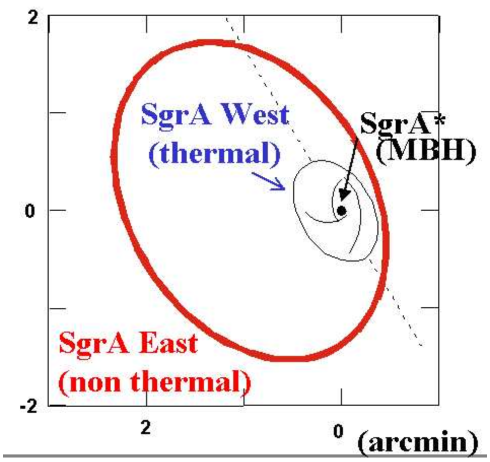
X-rays: collisional ionization of ISM by energetic electrons from arc.

Sgr A, I



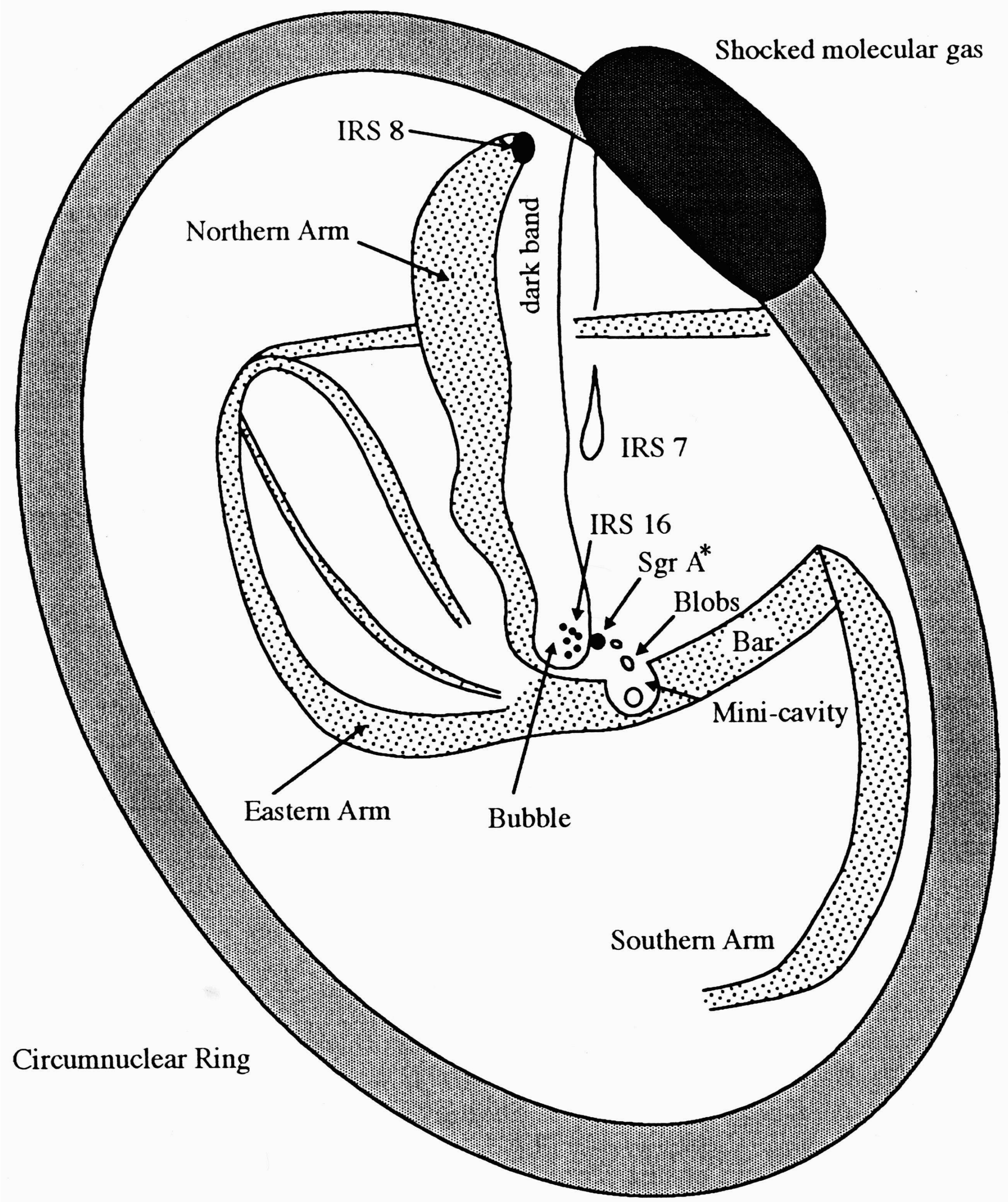
Sgr A West (courtesy K.Y. Lo)

Sgr A East: 8 pc diam, nonth. spectrum (powered by SNe?)



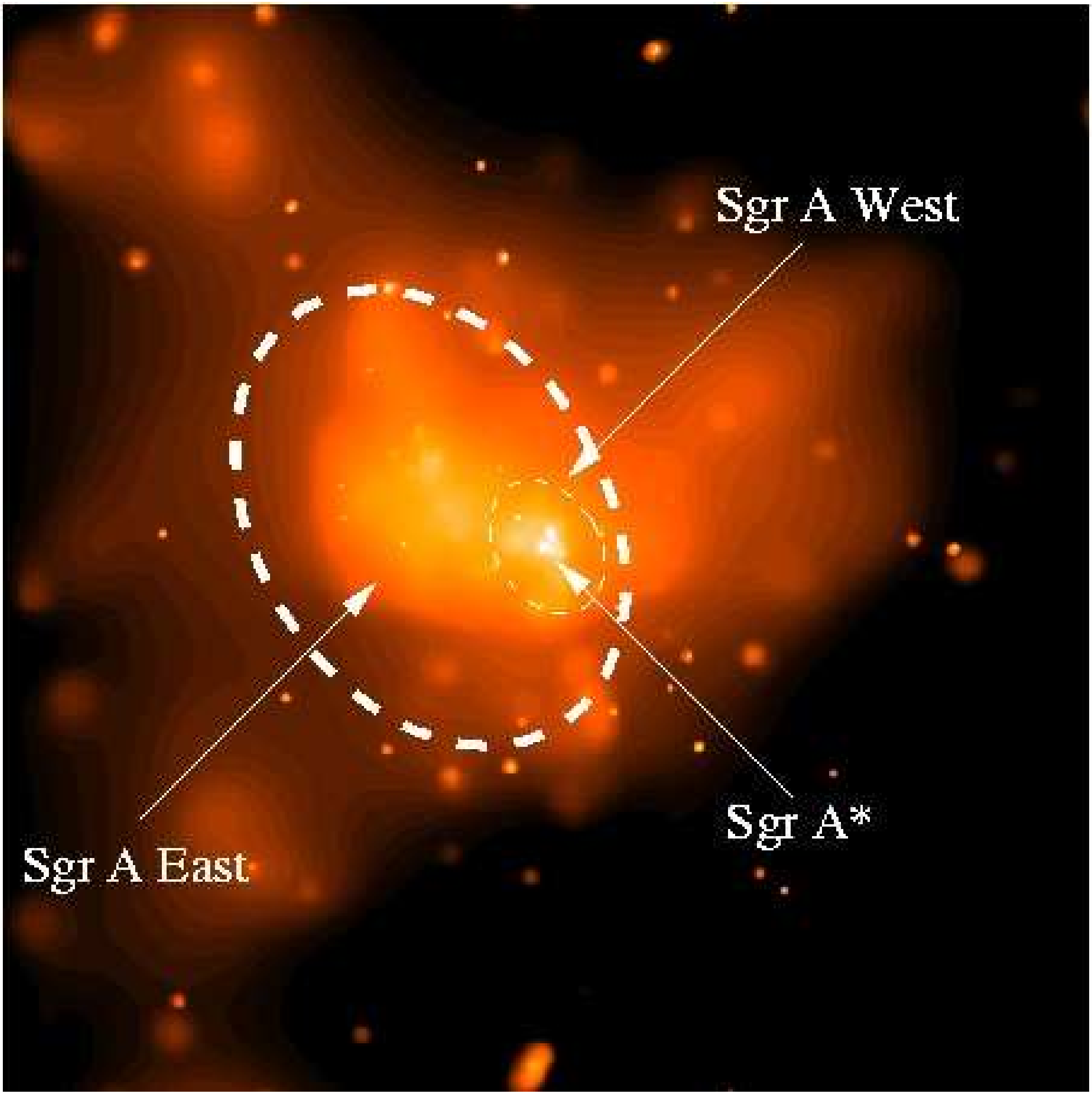
Sgr A West: “the spiral”: 2 pc diam, $\sim$ 60 $M_{\odot}$ ionized gas, tidally stretched out (also influence of mG B-field?), northern arm has infall, eastern arm and western arc rotate

Sgr A, II



Yusef-Zadeh, 1994

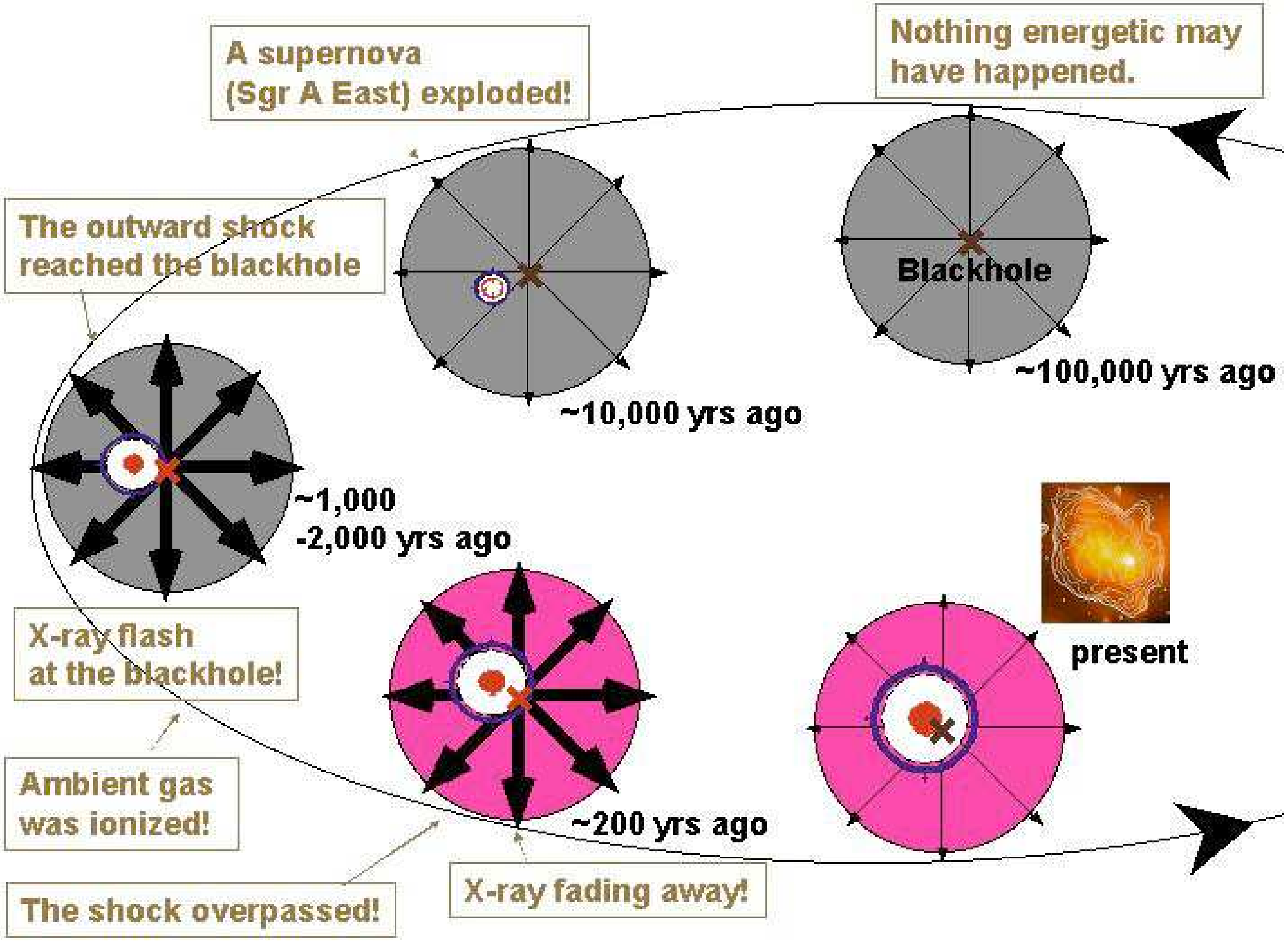
Sgr A, III



Chandra; Garmire et al., 2000; $8' \times 8'$

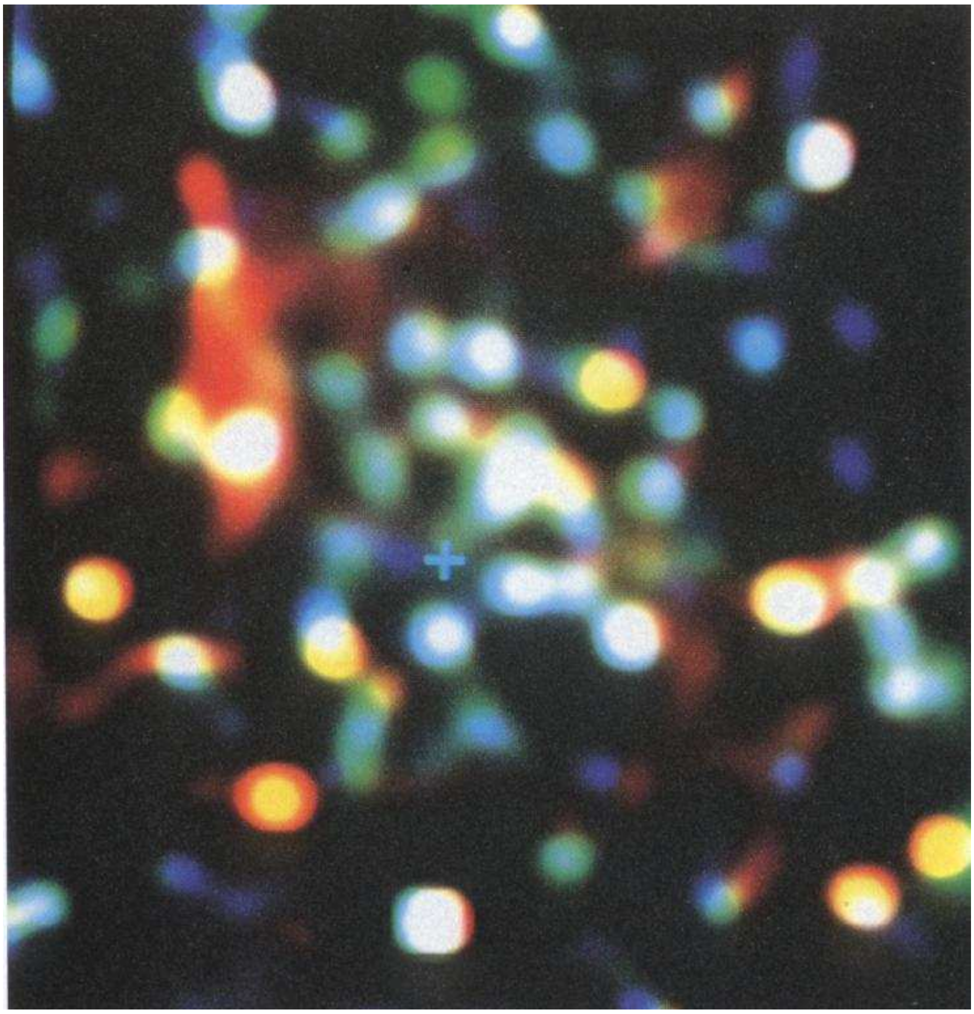
Around Sgr A: hot X-ray emitting gas ($kT \sim 10^7$ K) within radio cavity $\Longrightarrow$ heating by supernovae

Sgr A, IV



Garmire/Baganoff/Yusef-Zadeh, 2000

Sgr A, V



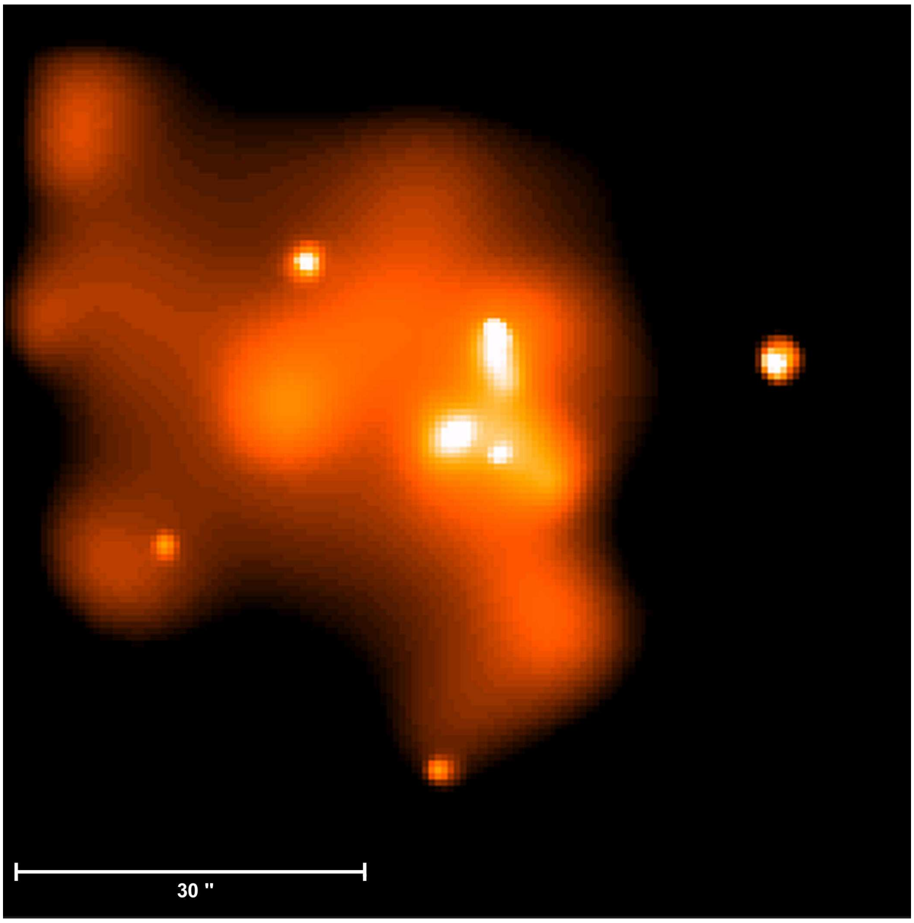
Center of Sgr A contains massive and dense star cluster ($> 10^6\,\mathrm{M}_\odot\,\mathrm{pc}^{-3}$, compare to solar neighborhood: $0.1\,\mathrm{M}_\odot\,\mathrm{pc}^{-3}$)

$+$: Position of Sgr A* $\Longrightarrow$ GC is IR-quiet!

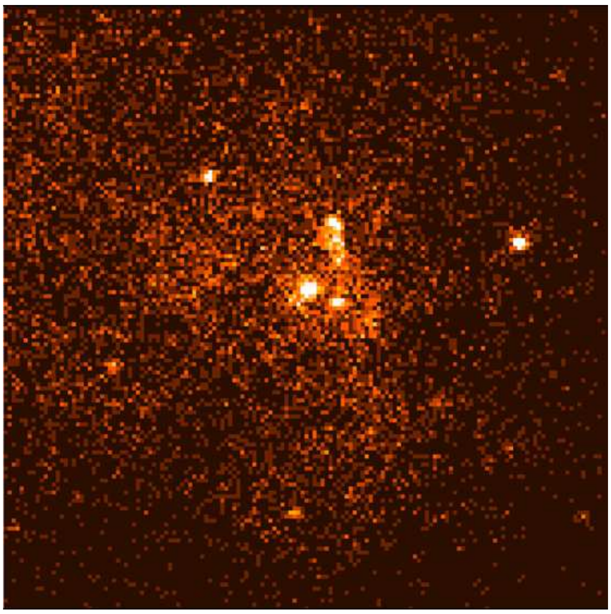
Brightest source: IRS 16.

Stars are helium-rich, early type, strong winds ($v_\mathrm{wind} \sim 1000\,\mathrm{km\,s}^{-1}$).

Sgr A*



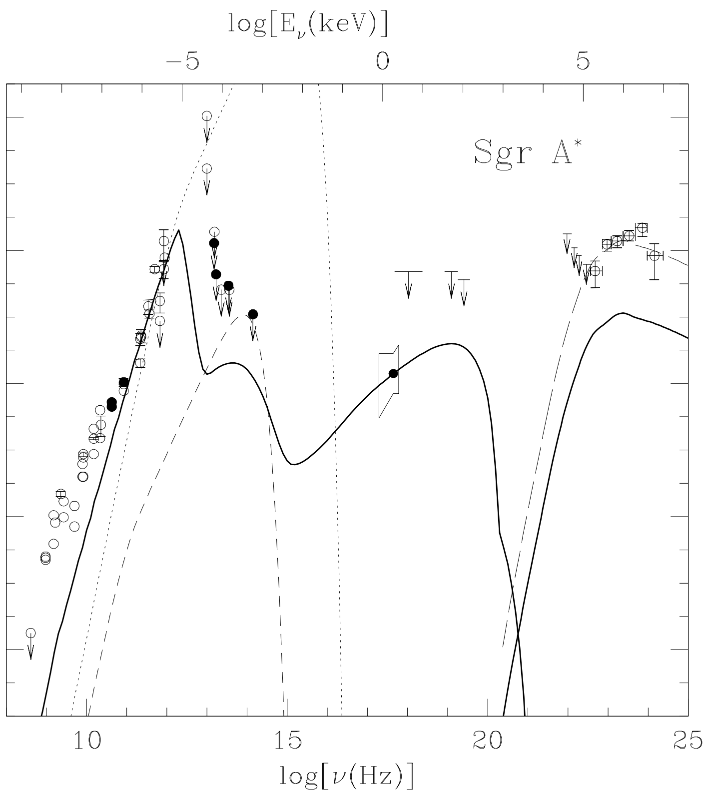
Baganoff et al., 2000



GC itself (=Sgr A*) is only a very weak X-ray emitter

Above image produced using adaptive smoothing. Image at left shows individual photons. . .

Sgr A*



Narayan et al., 1997

Radio: Upper limit for size of Sgr A*: 10^{13} cm!

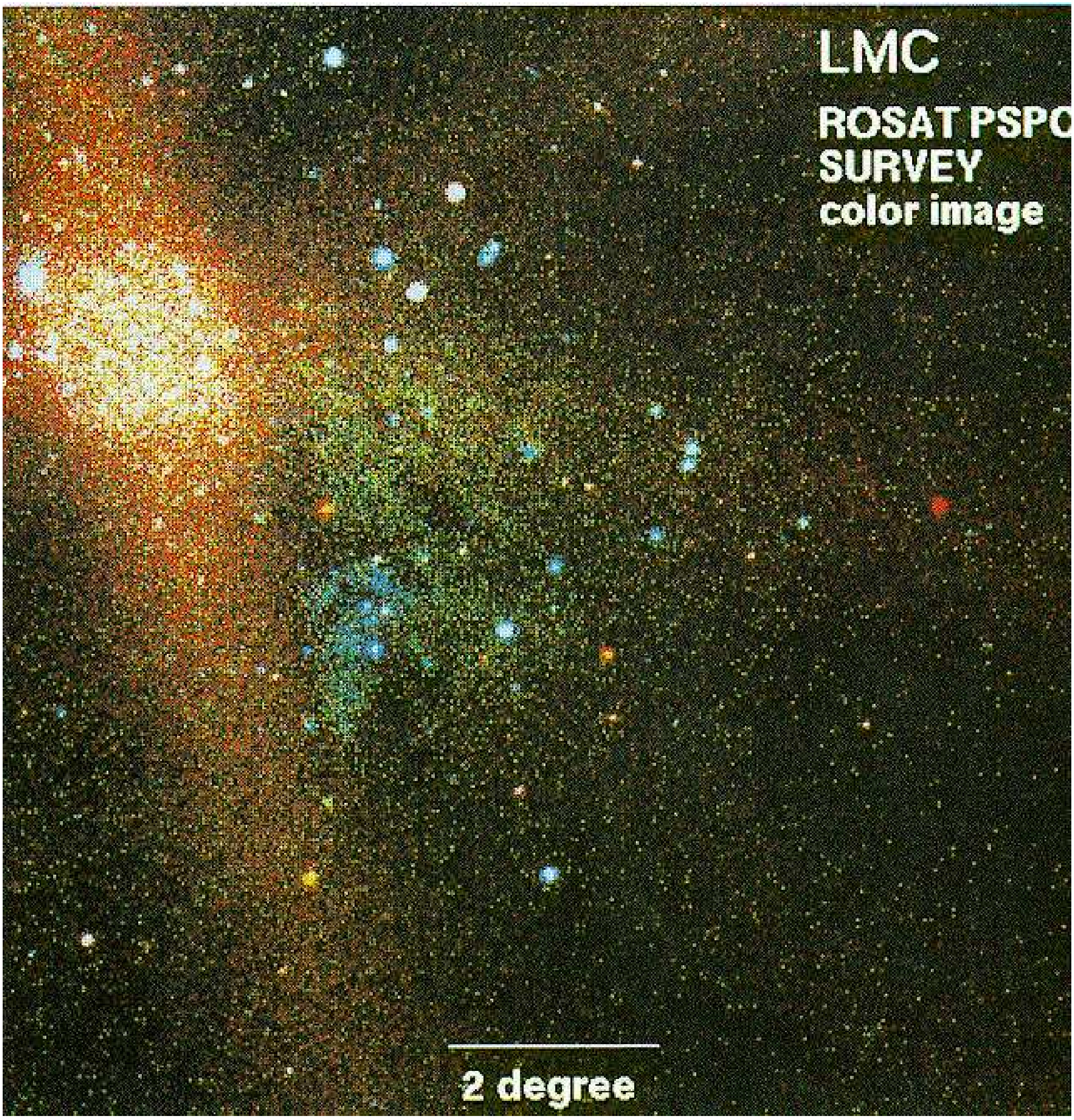
Bolometric luminosity: X-ray: 2×10^{36} erg s^{-1}, IR: 10^{38} erg s^{-1}, radio: 10^{34} erg s^{-1}

Mass from proper motion: $2.4 \times 10^6\,M_\odot$.

Compare to Eddington Luminosity $L_{\mathrm{Edd}} = 4 \times 10^{44}$ erg s^{-1}
$\Longrightarrow$ subcritial accretion!

Inferred mass accretion rate: $\dot{M} \lesssim 8 \times 10^{-5}\,M_\odot\,\mathrm{yr}^{-1}$, depending on model, source of accreting material unclear (stellar winds?)

The Large Magellanic Cloud



The LMC, an irregular galaxy, from the RASS, colors are hardness ratio $(H-S)/(H+S)$; very red: Super Soft Sources.

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Super Soft Sources

Super Soft Sources (SSS) are X-ray binaries characterized by

- extremely steep thermal spectra, $T_{\mathrm{BB}} \sim 3 \times 10^5\,\mathrm{K}$
- high luminosity (close to L_{Edd} for $M = 1\,M_{\odot}$)

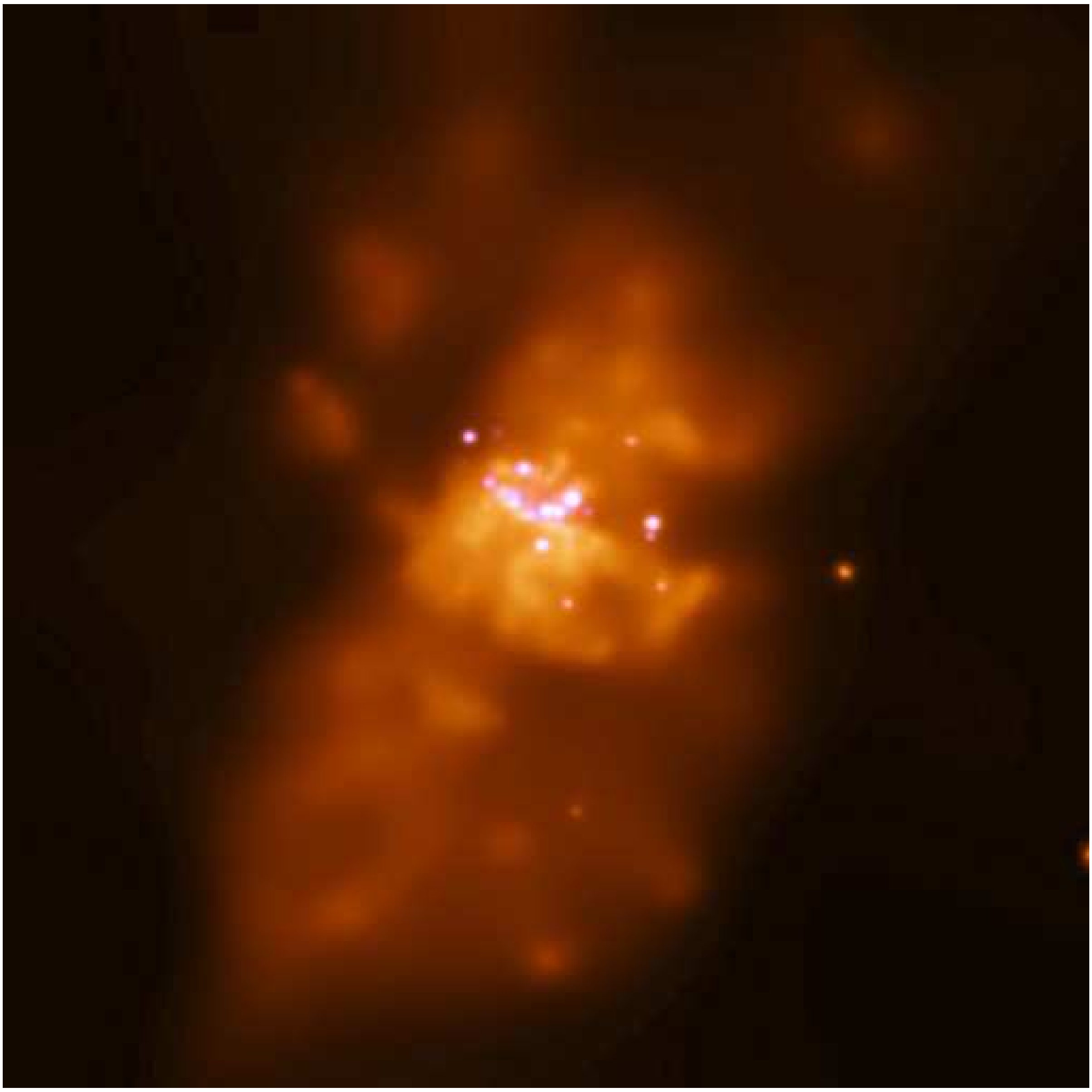
Five sources in the LMC (Cal 83, Cal 87, and others), two in the SMC, 15 in M31.

Theories for their nature (Kahabka, Pietsch & Hasinger (1994)):

- accretion disks around white dwarfs
- steady hydrogen burning on accreting WDs

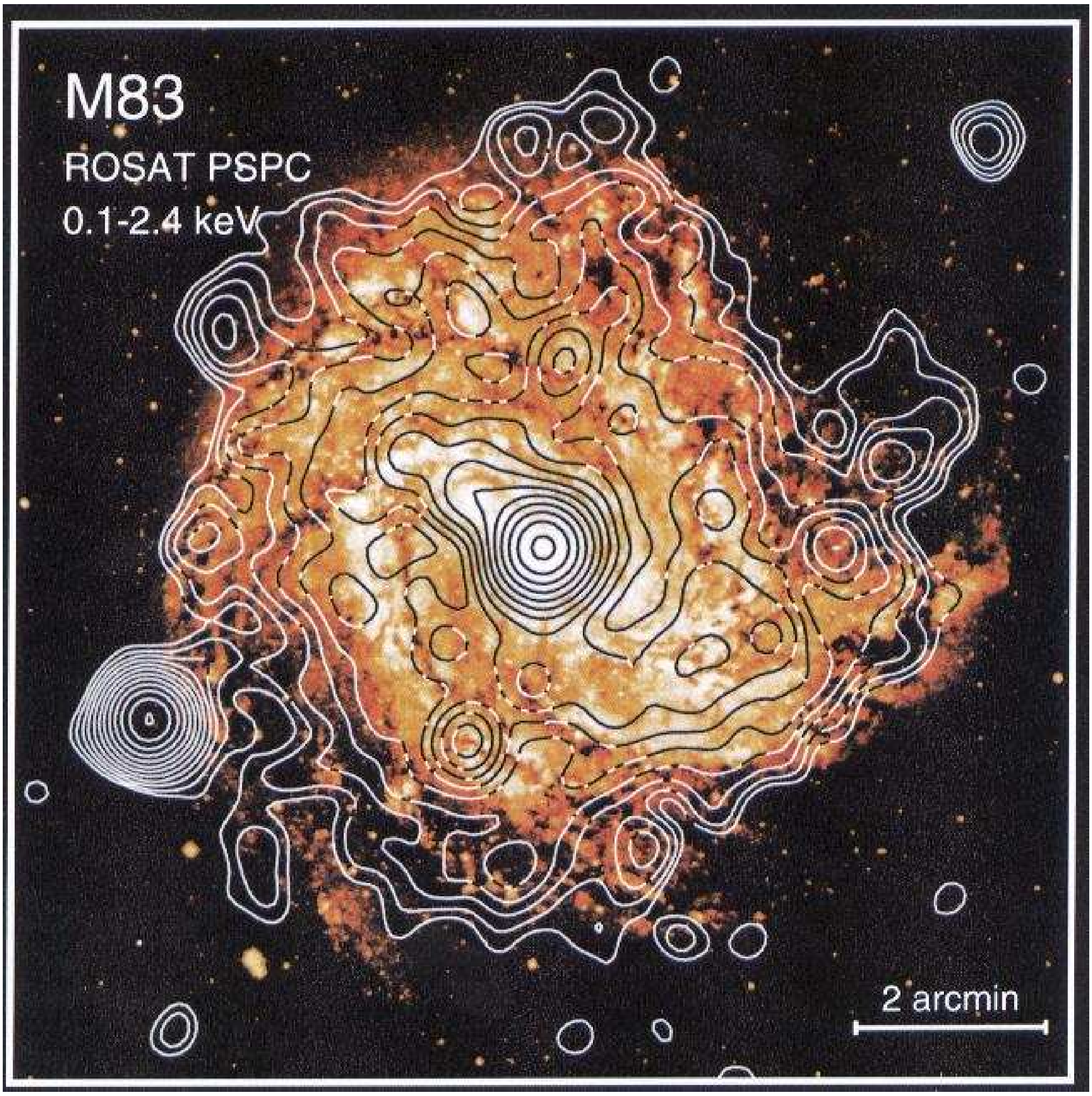
Other models appear to be ruled out due to the high luminosity.

M82, II



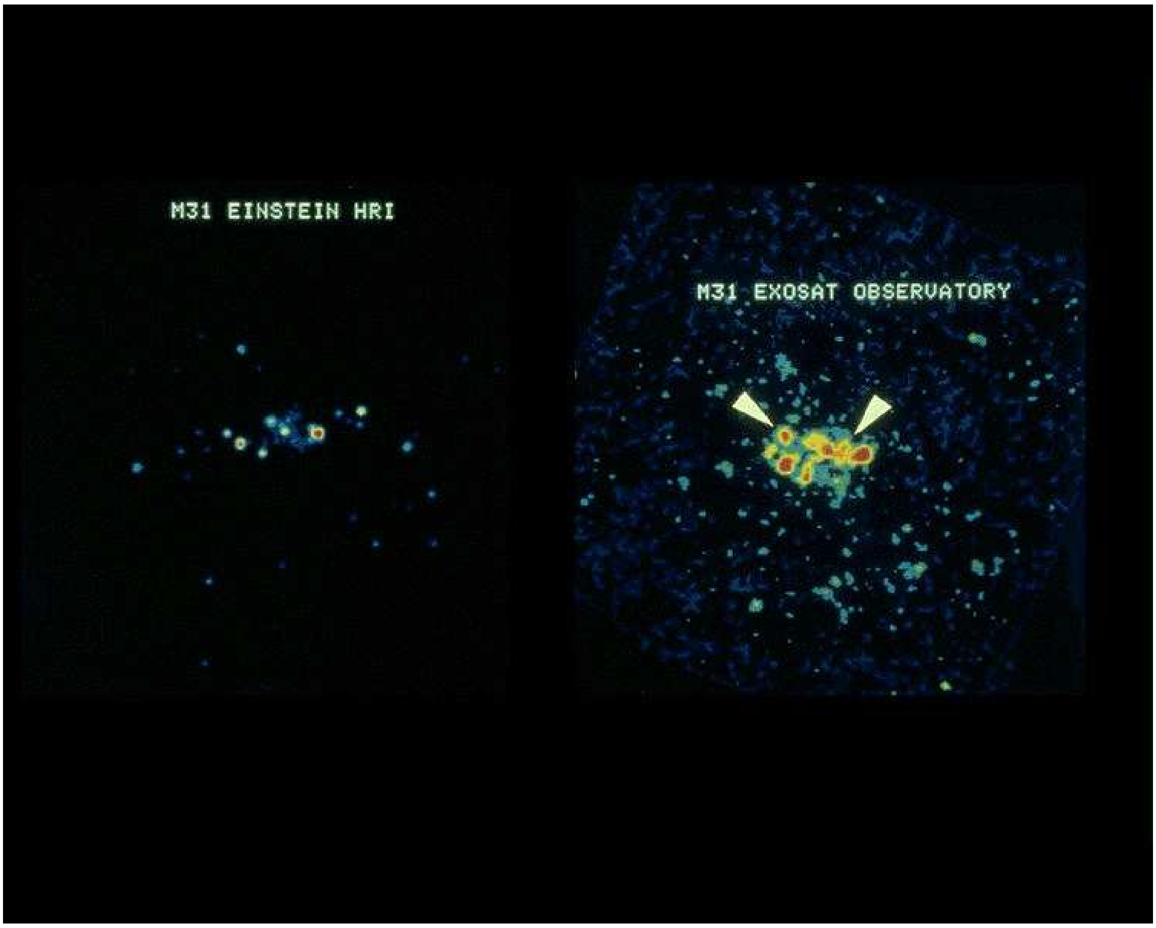
M82: XRBs in starburst region, hot gas flowing outwards.
(Starburst caused by close encounter with M 81?)

M83



M83, a spiral galaxy, optical image overlayed with X-ray intensity contours

Andromeda Galaxy, I



M31 as seen from *Einstein* and *EXOSAT*.

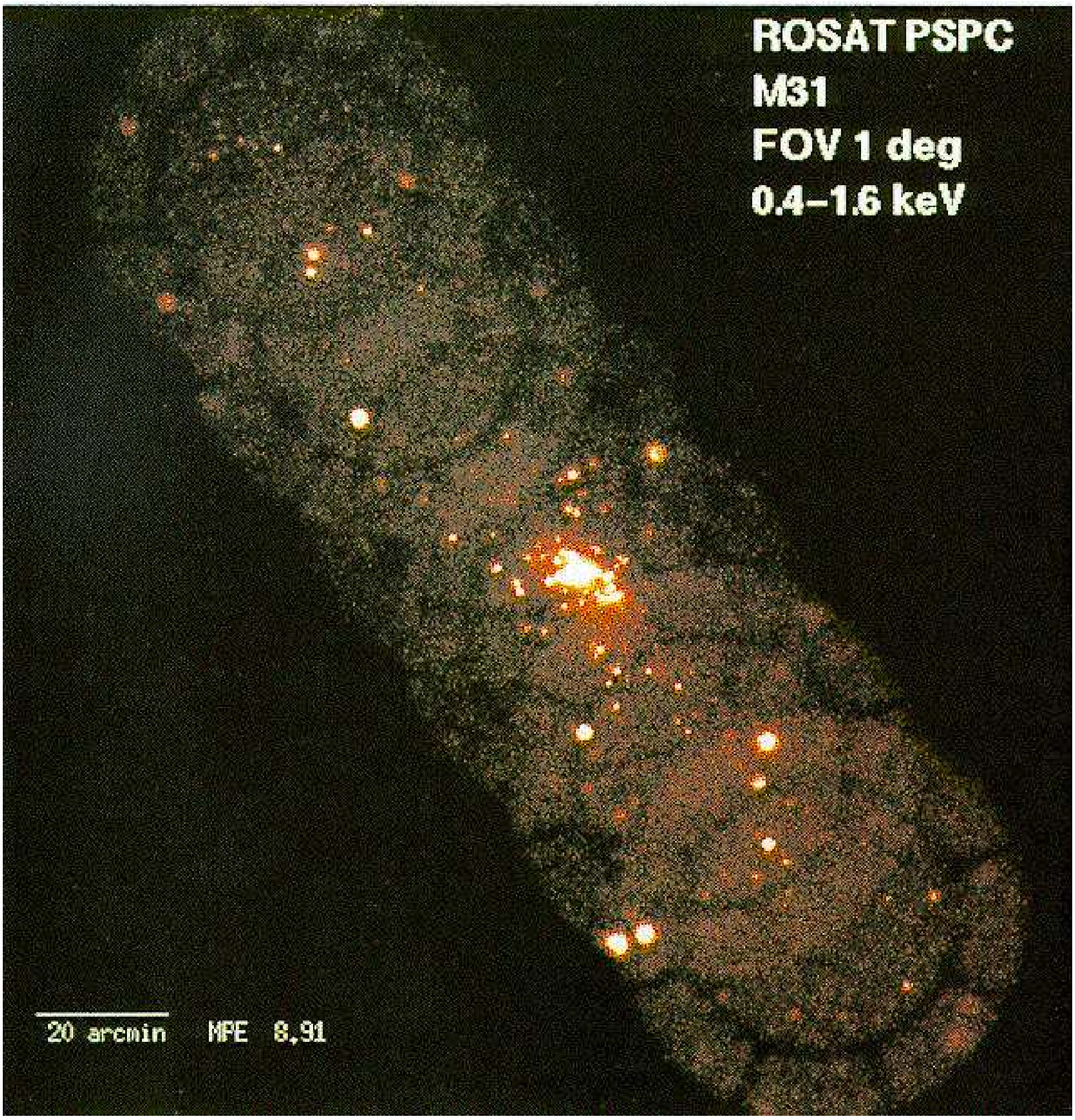
Andromeda nebula: At $d = 690\,\mathrm{kpc}$ closest spiral galaxy to milky way.

First studies of Andromeda nebula with early imaging instruments.

Einstein: 108 individual point sources, L_X between $5 \times 10^{36}\,\mathrm{erg/s}$ and $> 10^{38}\,\mathrm{erg/s}$ (Trinchieri et al., 1991), a few coincidences with SNRs.

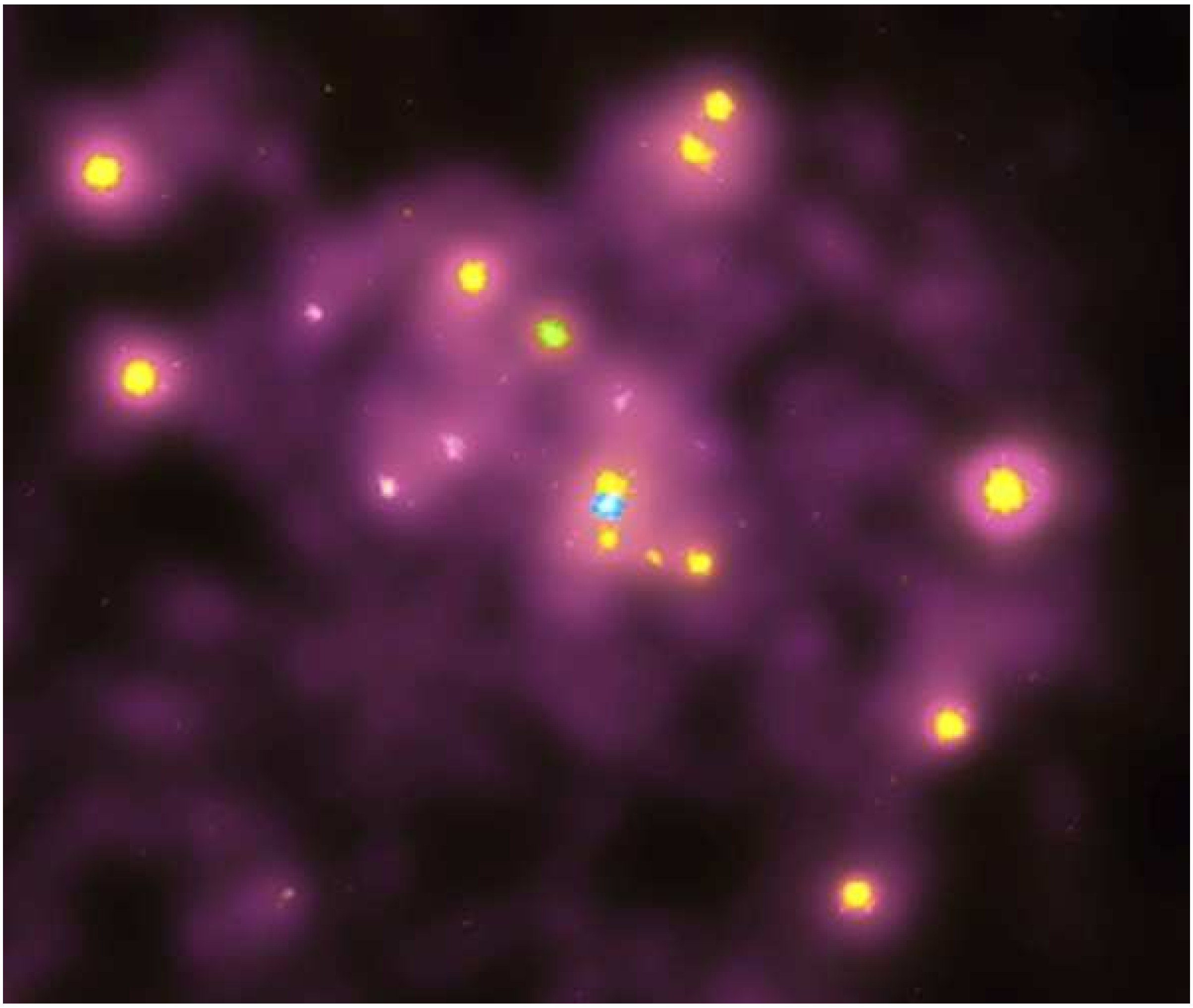
Total X-ray luminosity: 3×10^{39} erg/s

Andromeda Galaxy, II



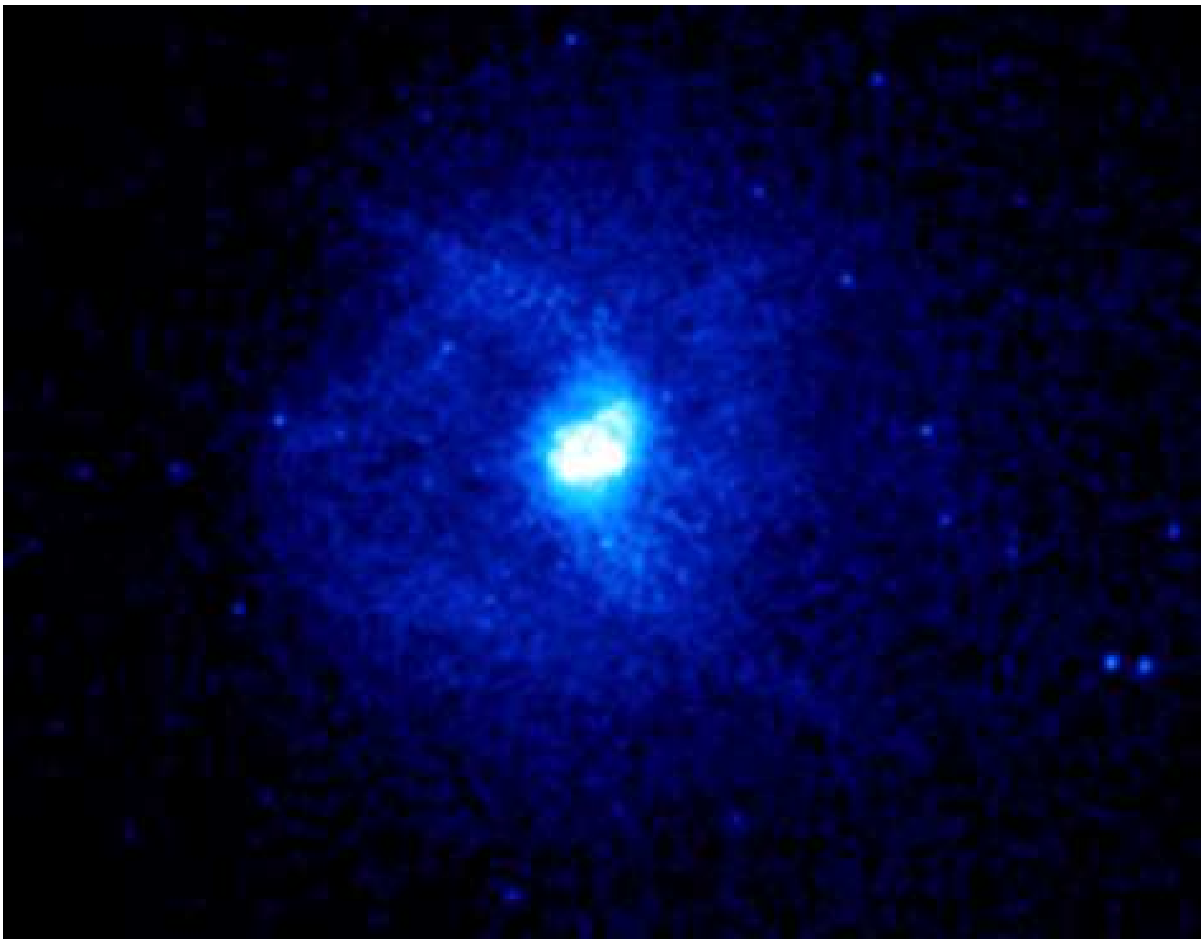
M31, different deep ROSAT pointings (note characteristic PSPC fingerprints; Supper et al. (1997)). About 400 sources detected, 50 of which are foreground (more than in *UHURU* catalogue!). Spectra or hardness ratios are compatible with accreting objects ($\Gamma \sim 2$, $N_{\mathrm{H}} \sim 10^{21}\,\mathrm{cm}^{-2}$); 15 SSS found; residual diffuse emission from hot gas.

Andromeda Galaxy, III



Center of Andromeda with Chandra: blue: very soft source close to supermassive black hole in center ($M \sim 10^7\,M_\odot$); other sources: XRBs

NGC 4636



NGC 4636: shock wave propagating outwards from galactic center (fed by outbursts from supermassive black hole?)

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Kahabka, P., Pietsch, W., & Hasinger, G., 1994, A&A, 288, 538

Supper, R., Hasinger, G., Pietsch, W., Trümper, J., Jain, A., Magnier, E. A., Lewin, W. H. G., & van Paradijs, J., 1997, A&A, 317, 328