

High Energy Astrophysics

- ◆ Course web page: <https://users.utu.fi/jurpou/teaching/>
- ◆ Lectures on Tuesdays 12-14, Wednesdays 14-16 and exercises on Fridays 12-14
- ◆ Lecturers: Juri Poutanen, Alexandra Veledina, Sergey Tsygankov:
e-mail firstname.lastname@utu.fi
- ◆ Teaching assistant: Anastasiia Bocharova : anboch@utu.fi
- ◆ "Office" hours: after lectures
- ◆ Course material: Lecture notes and books "Exploring the X-ray Universe" by Charles and Seward (chapters 1, 2, 7, 8, 10, 11, 12, 13, 14); some chapters from "Accretion Power in Astrophysics" by Frank, King, Raine and Shapiro & Teukolsky, White dwarfs, neutron stars and black holes.
- ◆ Home exercises: Compulsory homework sets will be assigned and due every week (you can either return them on paper in class or by email to the assistant). You are urged not to start these the night before they are due. For late exercises only one half of the points will be given.

The most important thing you can learn from homework is how to solve problems yourself. This is what you need to do to succeed in the real world. Therefore, please try each problem for at least 1 hour before discussing it with anyone else. Please, write your homework solutions in an extremely clear manner. It will not be possible to give credits for work that is not clearly explained. Please, show your work even if you cannot solve the whole problem, since this will allow partial credit to be given. When it is relevant, use general formulae as long as possible and only plug in numbers at the end of a problem.

- ◆ Computer exercises (bonus)
- ◆ Presentation (20 min) on one of the following topics (or even you can suggest your own). You will need to split to about 10 groups, 2-3 students in each.

1. Ultraluminous X-ray sources (ULX)
2. High energy neutrinos
3. Fast Radio Bursts
4. Magnetars
5. Black hole imaging (Event Horizon Telescope)
6. Gravitational waves from mergers
7. ULX pulsars
8. Gamma-ray bursts
9. Ultra-high energy cosmic rays (UHECR)
10. Relativistic effects in pulsar binaries
11. Particle acceleration in shocks
12. Sgr A* and the central parsec of the Milky Way
13. Novae

- ◆ Exam: There will be two questions from the required reading as well as two problems from the set of home exercises. No help from the books, lecture notes, or any other material is allowed during the exam (1 A4 page is allowed). A standard non-programmable calculator could be used.
- ◆ Grading: Your grade will be based on homework - 20%, presentation - 10% and the final exam - 70%.
- ◆ Requirements: Minimum 50% of exercises and the final exam.
- ◆ Additional points will be given for two computer exercises (course "Topical projects in research" FFYS7039)
- ◆ Questions and office hours: You may ask questions immediately after lectures. You can also send me your questions by e-mail. If you are unhappy with something, please let me know, I will try to fix it if possible. You are encouraged to ask questions during the lectures. Also, if I am lecturing too fast or something is not clear please feel free to tell me, and I'll be happy to go over some material again.

cgs (cm/gram/second) units

Fundamental:

Gravitational constant, $G=6.679 \times 10^{-8} \text{ cm}^3/\text{g}/\text{s}^2$

Stefan-Boltzmann: $\sigma_{\text{SB}}= 5.6705 \times 10^{-5} \text{ erg}/\text{cm}^2/\text{s}/\text{K}^4$

Speed of light, $c=2.99792 \times 10^{10} \text{ cm}/\text{s}$

Electron mass: $m_e=9.109 \times 10^{-28} \text{ g}$

Proton mass: $m_p=1.6726 \times 10^{-24} \text{ g}$

Planck constant $h=6.626 \times 10^{-27} \text{ erg s}$

Electron charge: $e=4.803 \times 10^{-10} \text{ e.s.u.}$

Boltzmann constant: $k=1.380 \times 10^{-16} \text{ erg}/\text{K}$ or $8.617 \times 10^{-5} \text{ eV}/\text{K}$

Gas constant $R=8.314 \times 10^7 \text{ erg}/\text{mol K}$

Solar:

Radius $R_{\odot}=6.955 \times 10^{10} \text{ cm}$

Luminosity $L_{\odot}= 3.845 \times 10^{33} \text{ erg}/\text{s}$

Mass $M_{\odot}=1.989 \times 10^{33} \text{ g}$

Astronomical:

Parsec, pc: $3.085 \times 10^{18} \text{ cm}$

Astronomical Unit, AU: $1.496 \times 10^{13} \text{ cm}$

Miscellaneous

Energy of 1eV = $1.602 \times 10^{-12} \text{ erg}$ = 11,600 K (x k) = $2.418 \times 10^{14} \text{ Hz}$ (x h)

High-energy astrophysics

- ◆ High-energy astrophysics deals with compact objects where special and/or general relativistic effects are important.
- ◆ In these objects, the particles (electrons, positrons, protons) are heated/accelerated to relativistic energies and they emit high-energy photons (X-rays and gamma-rays) and possibly neutrinos.
- ◆ Many astrophysical objects emit radiation in a very wide range of energies from radio to the gamma-rays.
- ◆ One cannot learn much by looking only in one band.

Most powerful (steady) sources

- ◆ Most of extragalactic gamma-ray sources are blazars: active galaxies with relativistic jets pointing directly towards us.
- ◆ They produce luminosity of 10^{14} times the solar luminosity.



Active galaxies

Cen A
(distance ~ 2.5 Mpc)

HST & 6 cm VLA

Radio lobe size ~ 200 kpc!

The radio lobes are fed by relativistic jets; we see only one sided jet due to relativistic beaming.

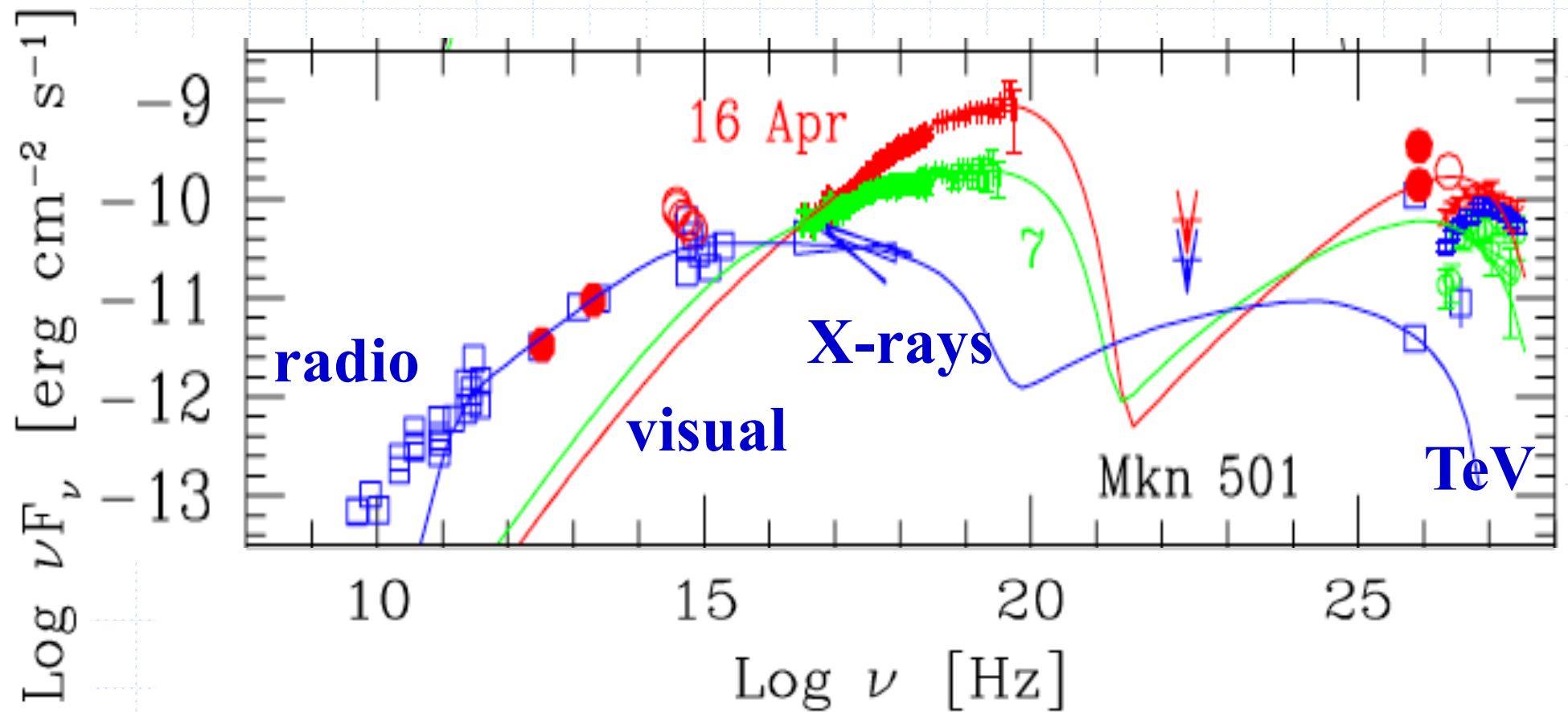


Gamma-ray image by
Fermi in pink.
Orange – radio

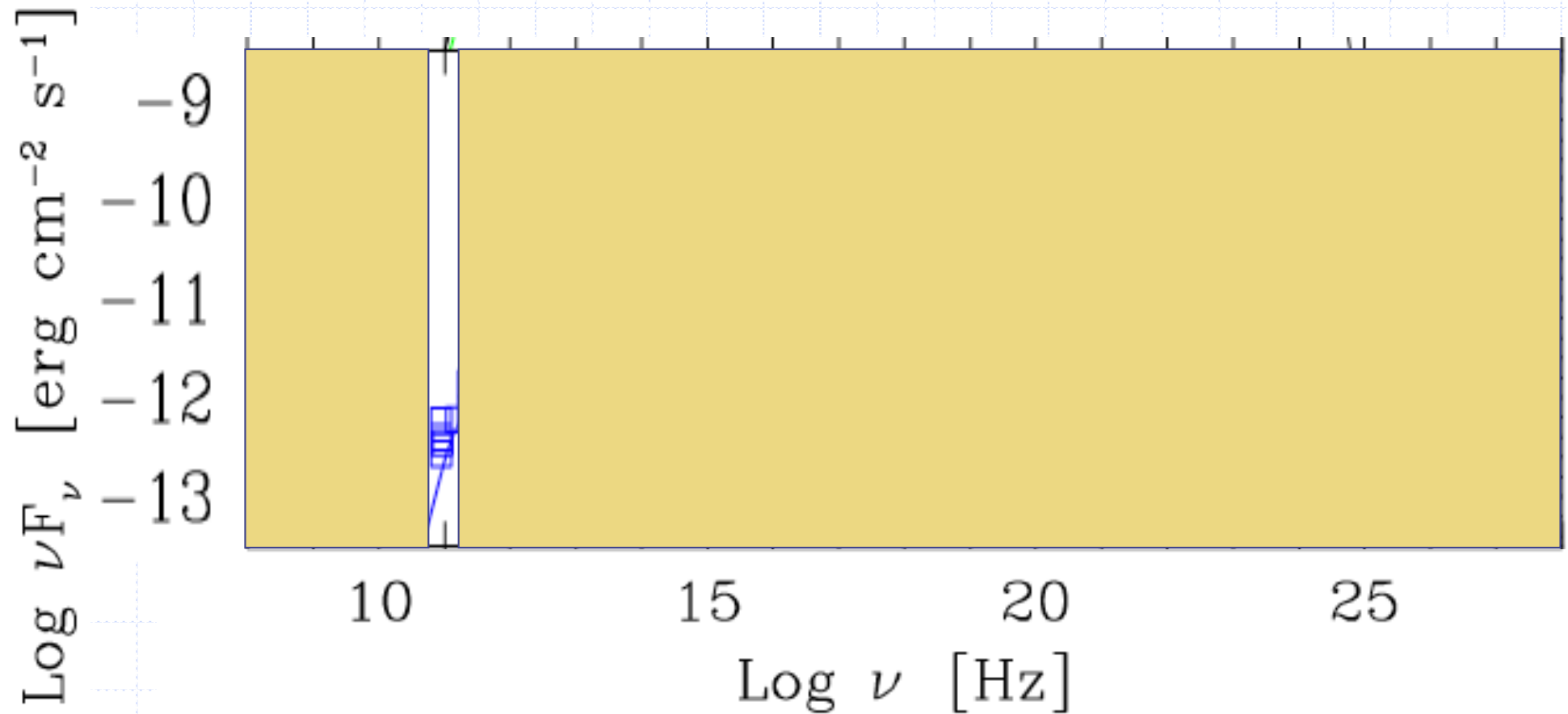


Blazars=

Active galaxies with relativistic jets

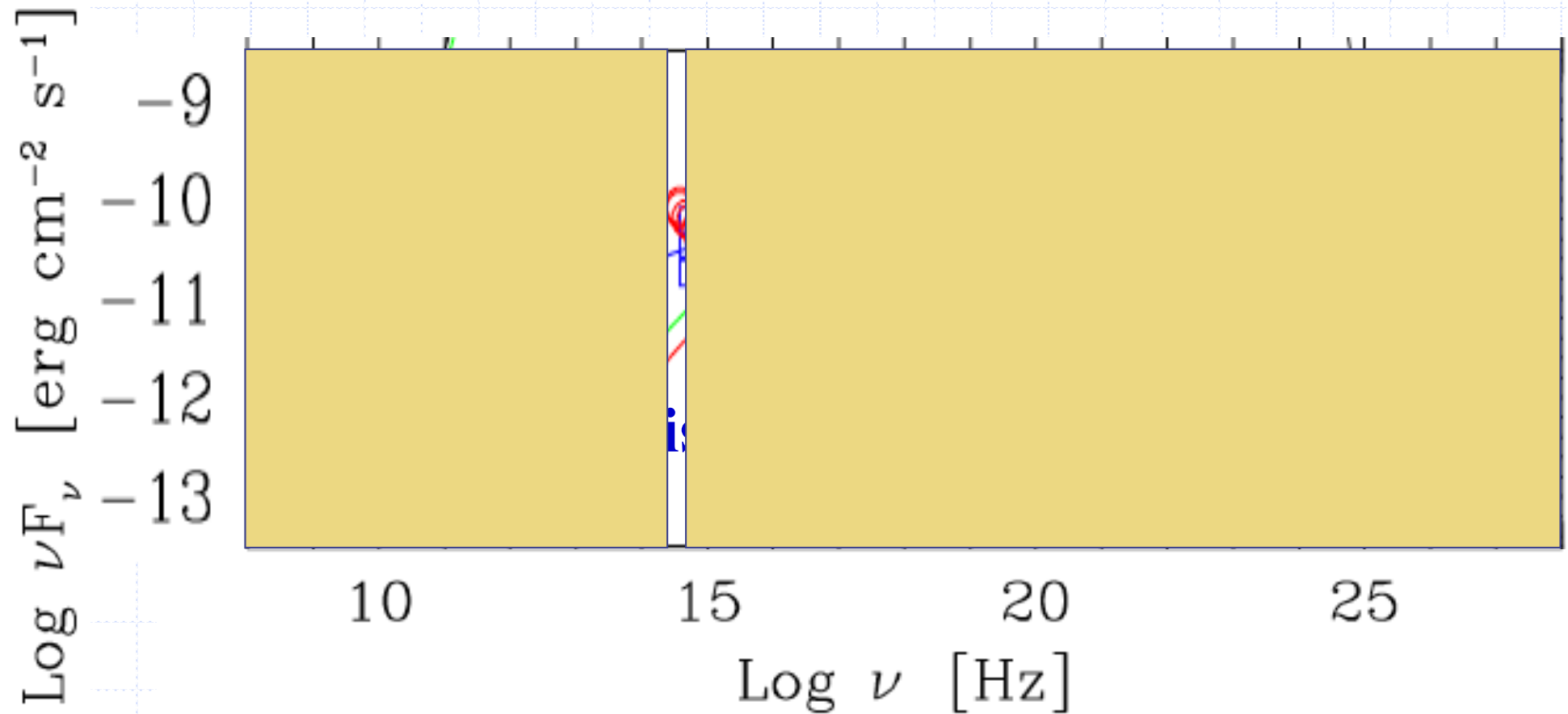


Blazars=
Active galaxies with relativistic jets



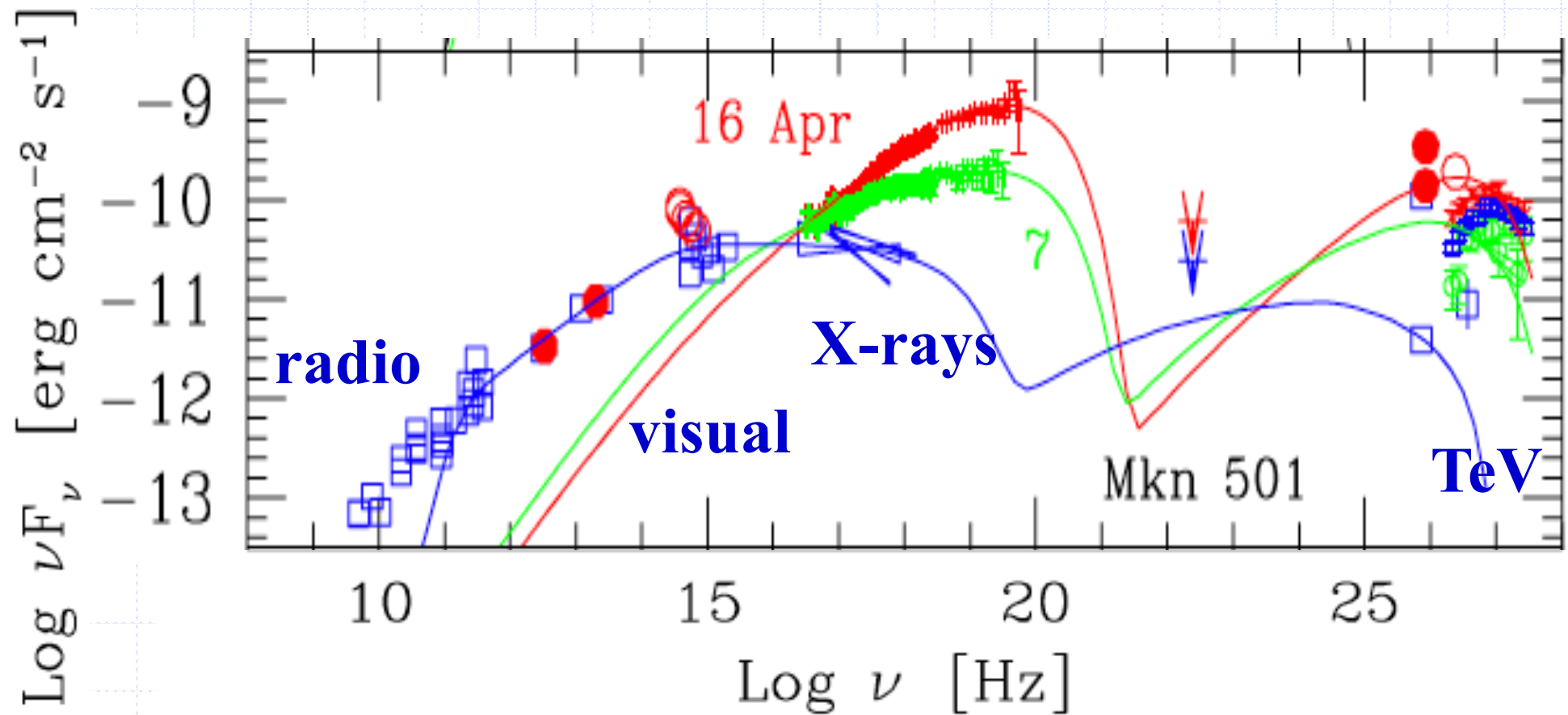
Blazars=

Active galaxies with relativistic jets



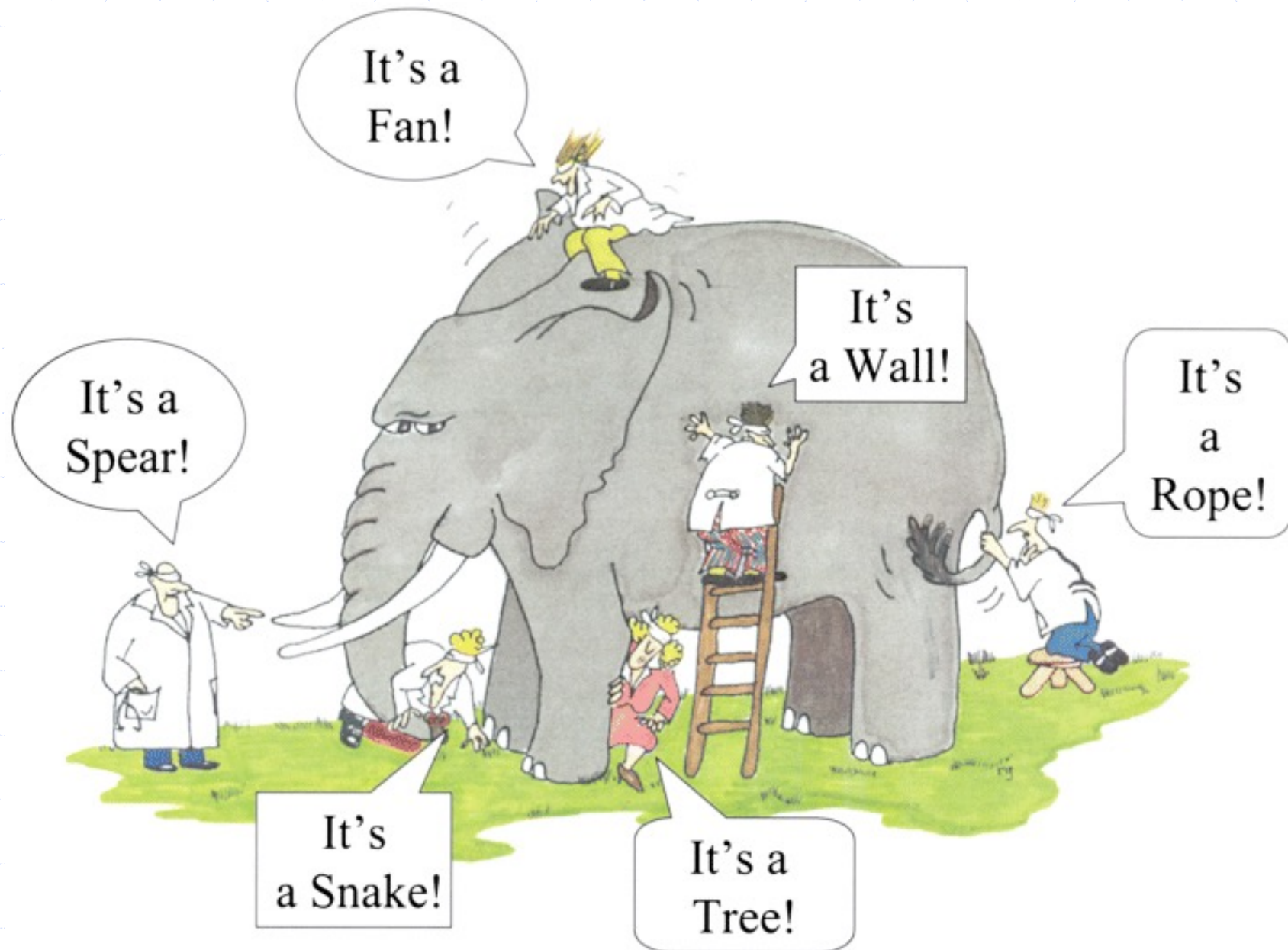
Blazars=

Active galaxies with relativistic jets



Multiwavelength studies are needed!

The Universe and the Elephant



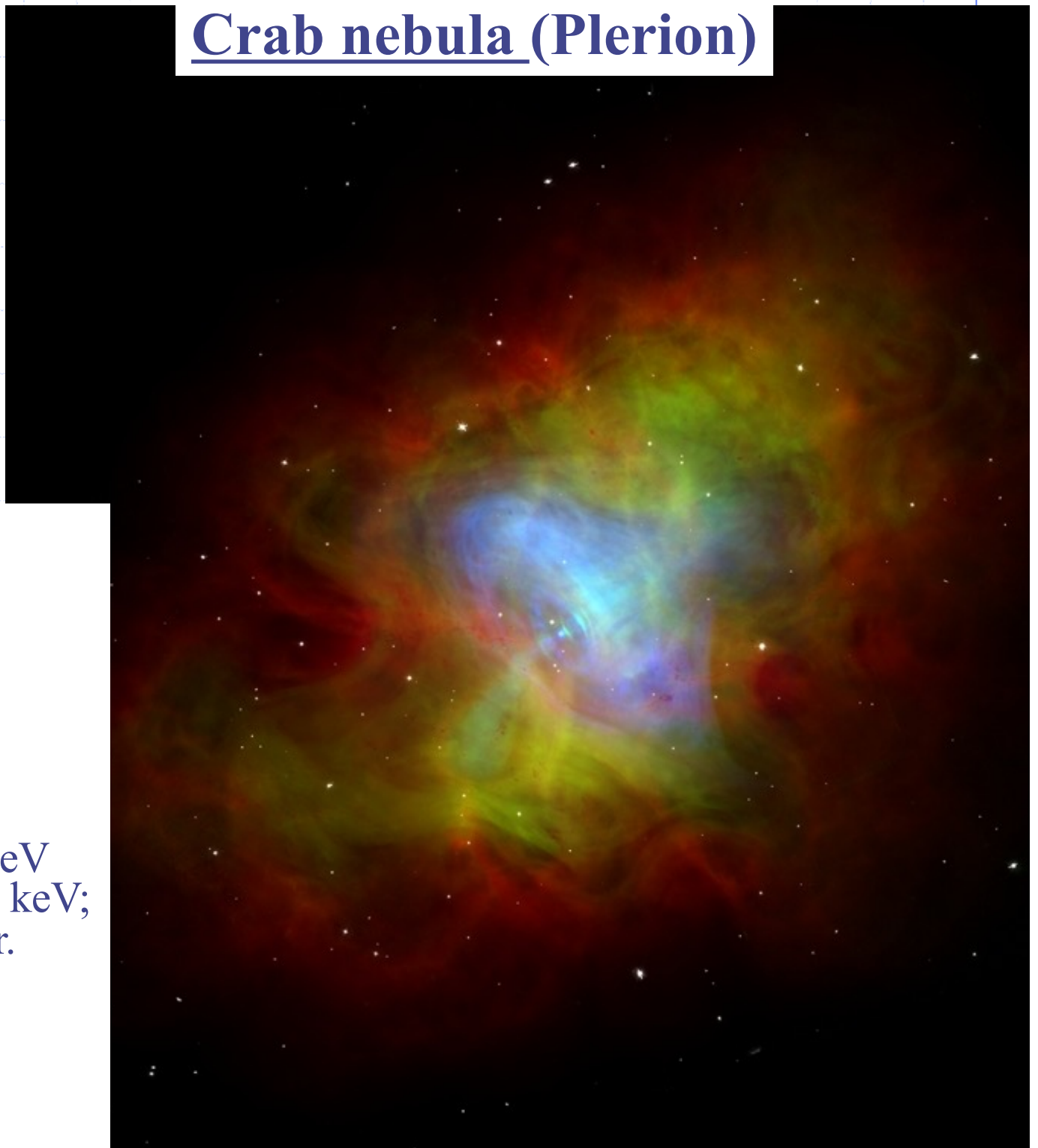
Crab nebula (Plerion)

Blue: X-ray
Red: optical
Green: radio

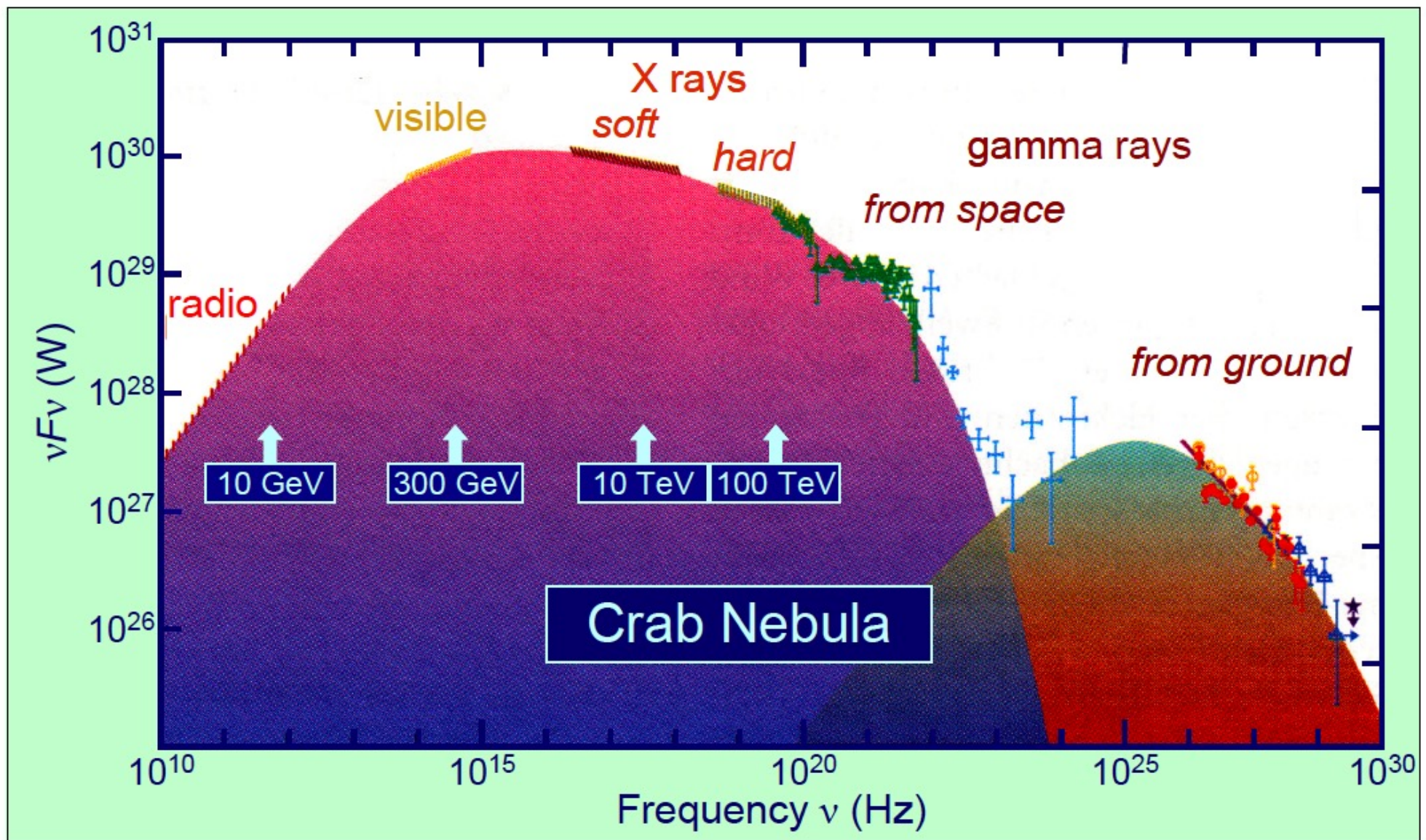
Luminosity $\sim 10^{38}$ erg/s
(mostly X-ray & gamma)

Synchrotron radiation
(linear polarization of 9%
averaged over nebula).

Electrons with energy $> 10^{14}$ eV
are needed for emission at 10 keV;
lifetime for these e^- 's < 1 year.
So electrons must be injected
continuously &
not come from SNe.

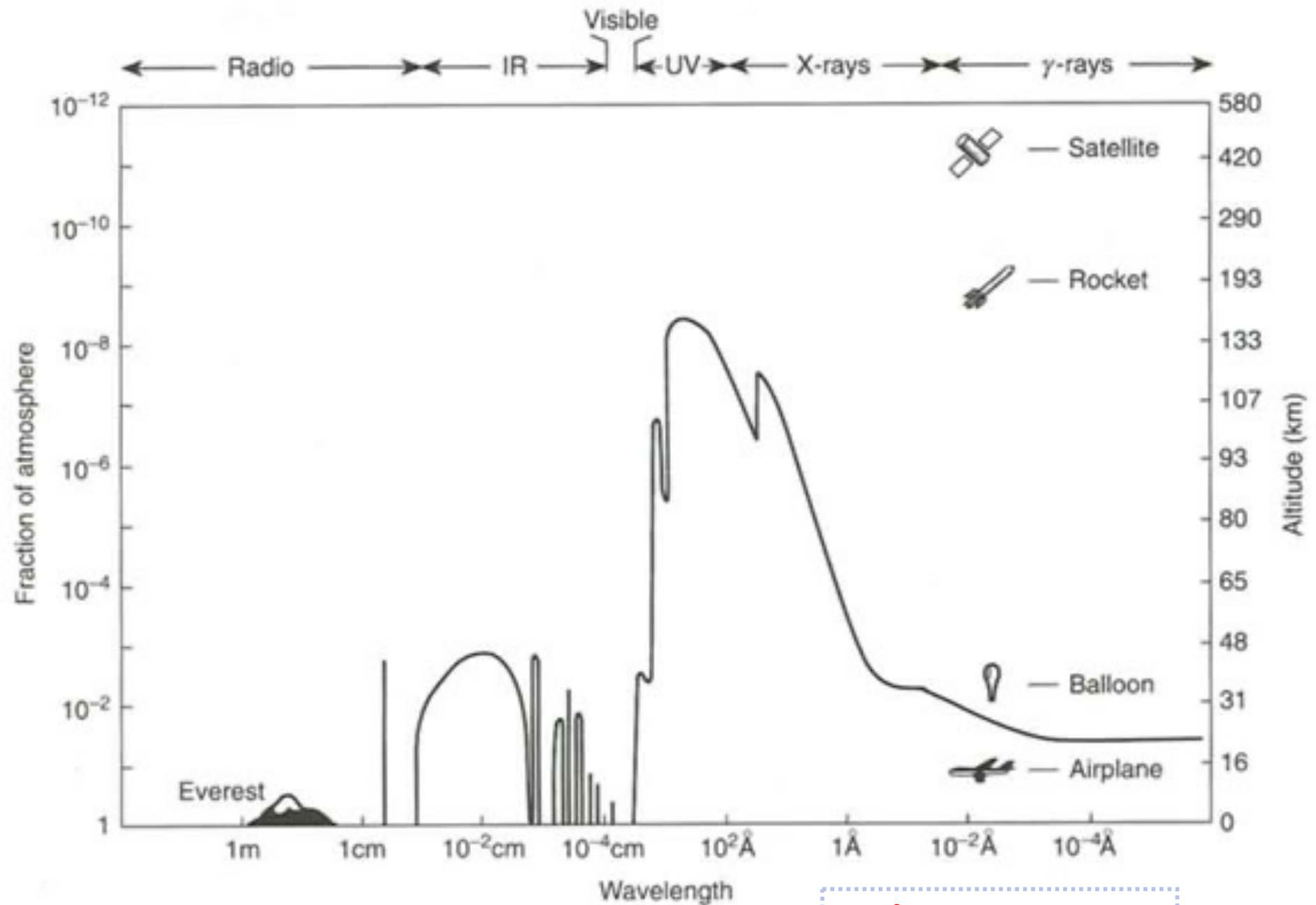


Crab nebula



← R, mm, IR, O, UV, X gamma-rays →

Transmission of the Earth atmosphere



($1\text{\AA} = 12.5 \text{ keV}$)

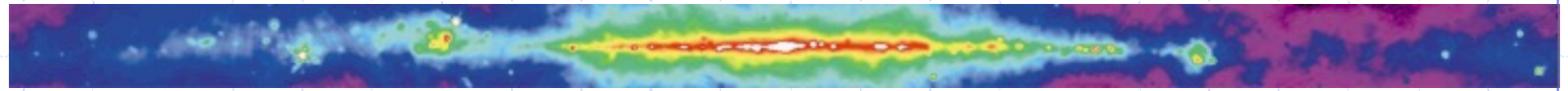
High-energy astrophysics

◆ What shall we learn today?

- ❖ The Universe (and the Milky Way) as viewed at different wavelengths. Common features.
- ❖ Penetrating power of the radio, X-ray and gamma-ray radiation.
- ❖ Distribution of the X-ray sources. Galactic X-ray sources: X-ray binaries, white dwarf binaries, active stars.
- ❖ Accretion as a source of energy. Efficiency of accretion.
The most efficient engines of the Universe.
- ❖ Various kind of black holes: stellar and supermassive.
- ❖ Active galaxies, galaxy groups and clusters.

Milky Way

Radio 0.4GHz



IR (12-100 μm)



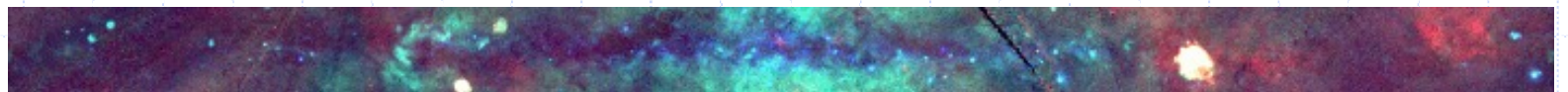
Near IR (1-4 μm)



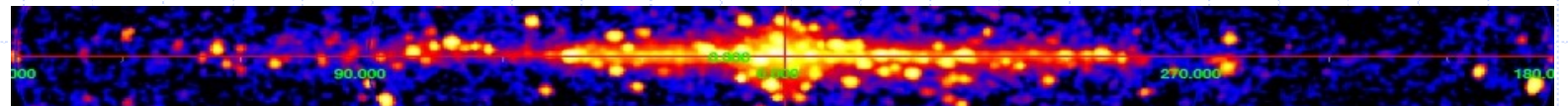
Optical



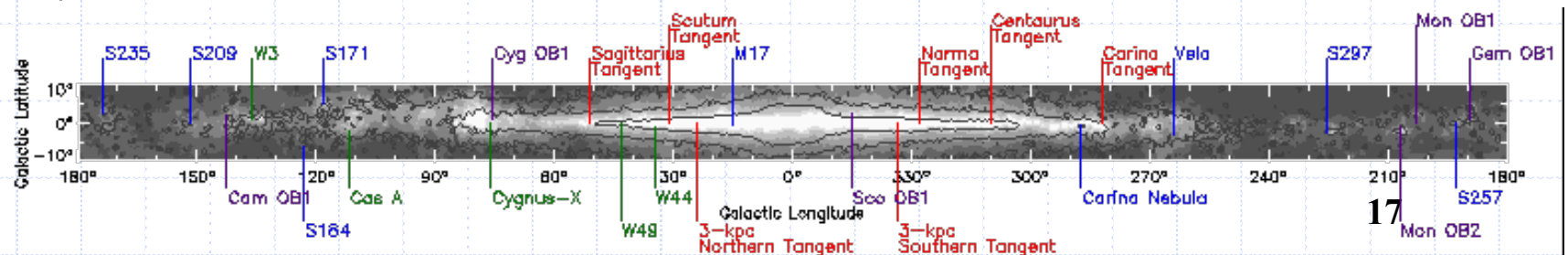
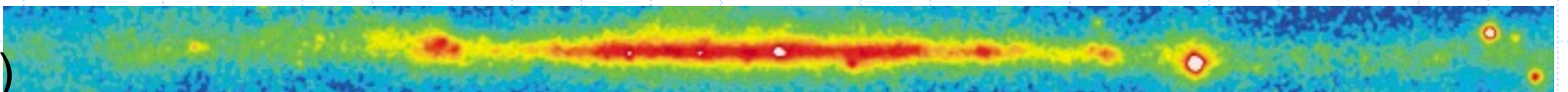
X-rays (1keV)



X-rays (20 keV)

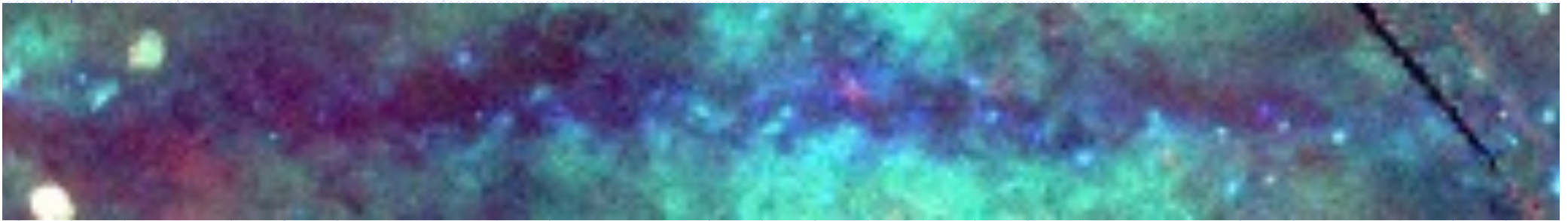


γ -rays (300 MeV)



Milky Way

Optical

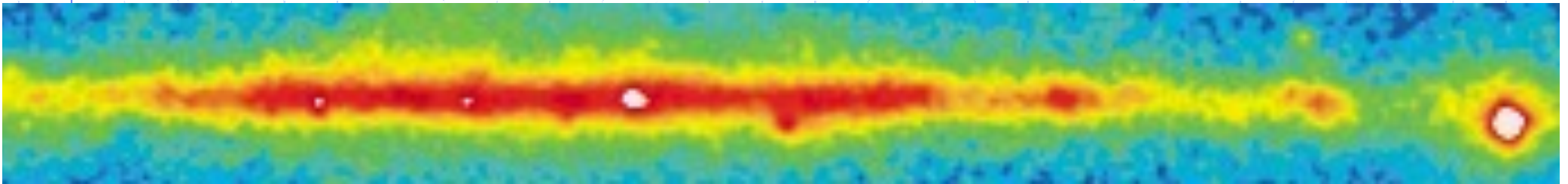
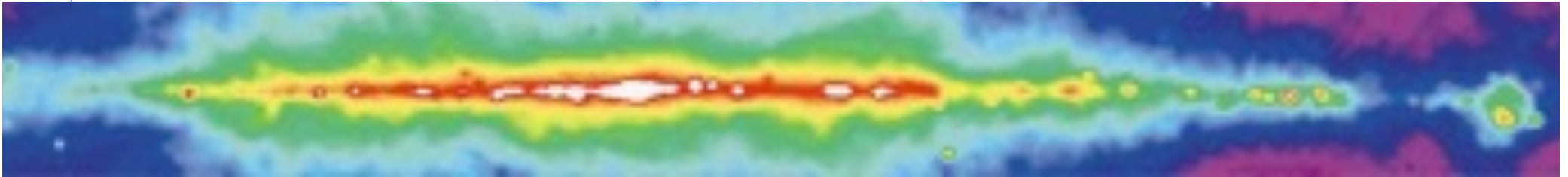


X-rays (1keV)

**Dust absorbs radiation both in
optical and soft X-rays**

Milky Way

Radio (0.4GHz)

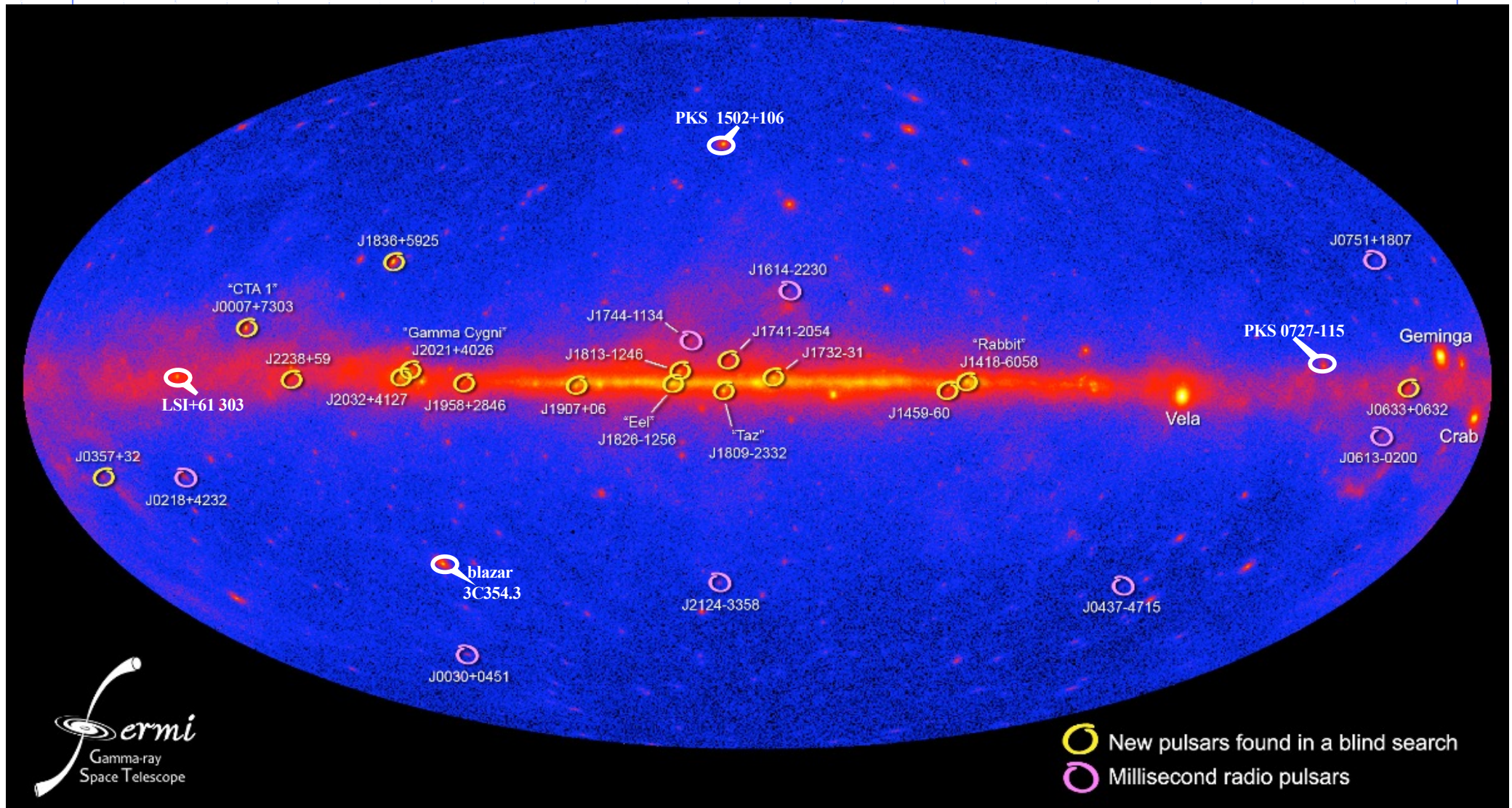


γ -rays (300 MeV)

Milky Way is transparent in radio and gamma-rays

**Relativistic particles emit both in
radio and gamma-ray bands**

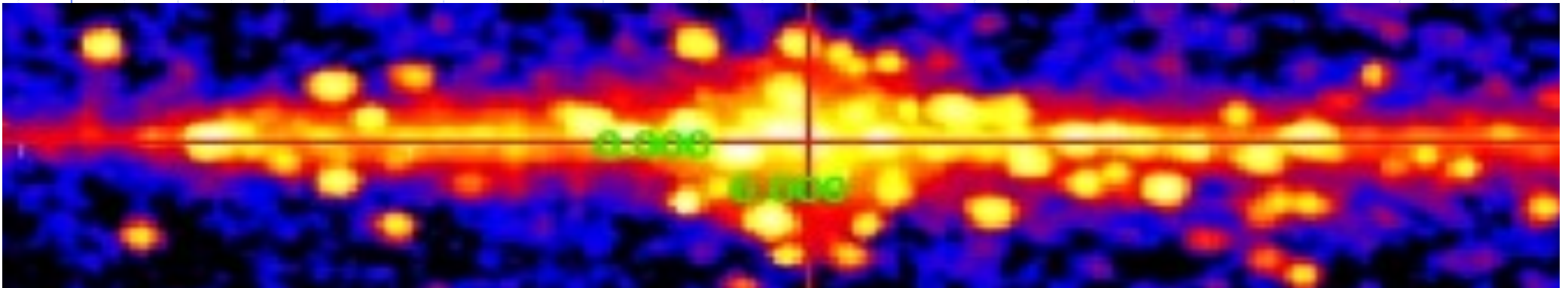
Fermi (2008-) all-sky survey in 100 MeV- 100 GeV



Extragalactic sources are mostly active galaxies

Milky Way

Near IR (1-4 μm)



X-rays (20 keV)

Milky Way is also transparent in IR and hard X-rays.

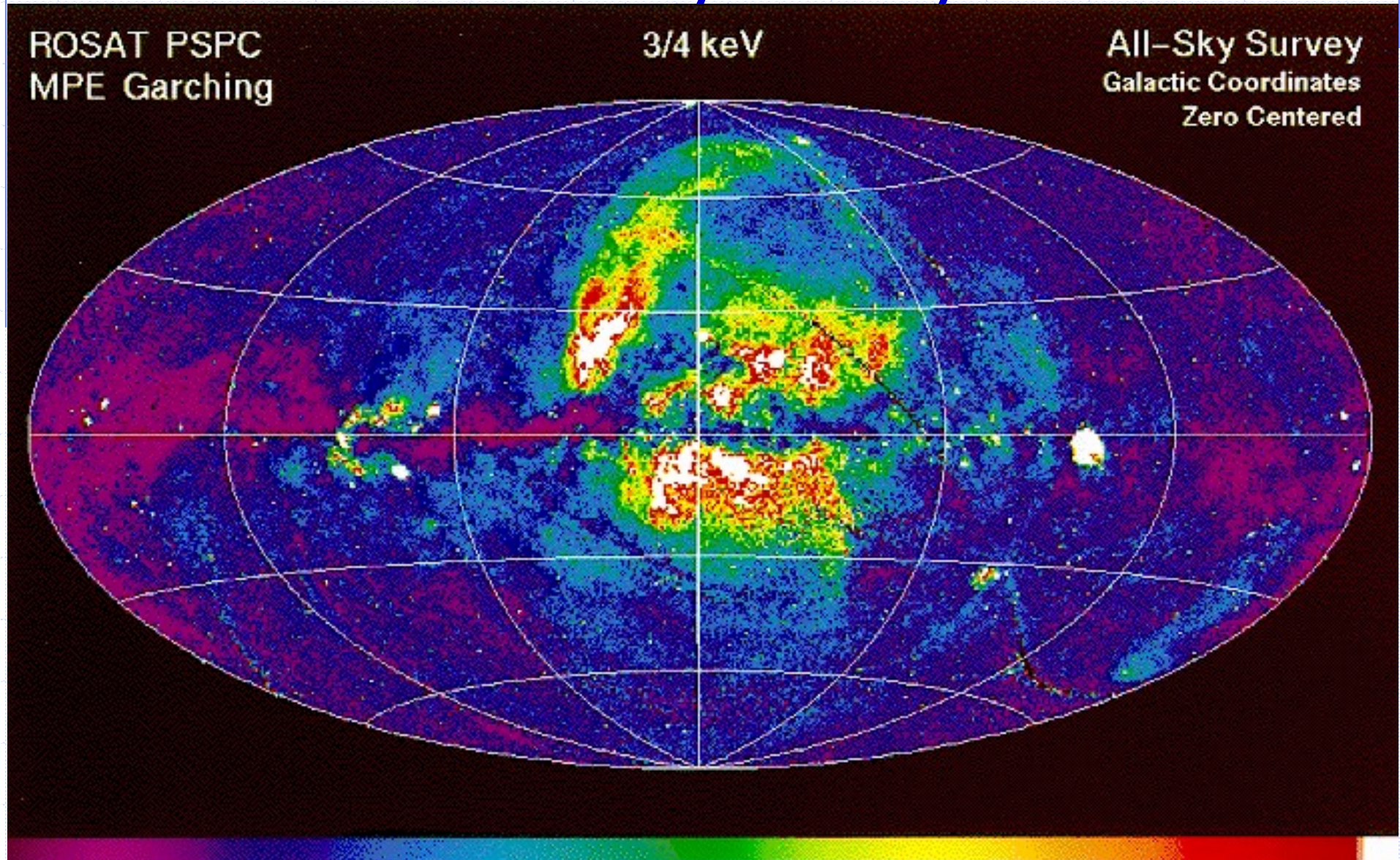
X-ray sources are distributed similarly to the old stellar population (red stars).



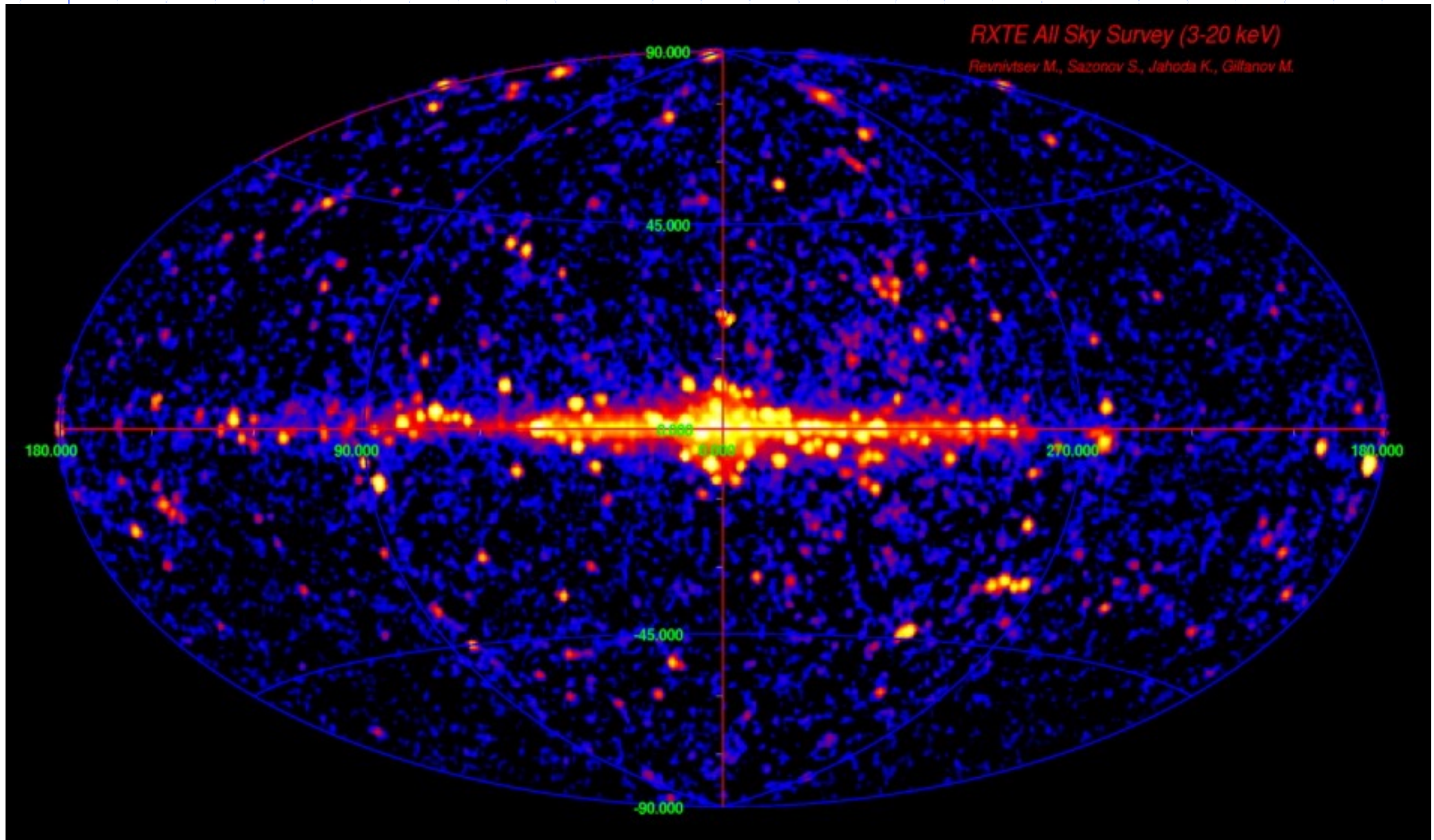
Roentgen's original plate of a man with keys in his pockets. (Deutsches Museum, Munich)

1. The Universe is more or less transparent in the X-ray and gamma-ray bands, because it is made mostly of light elements.
2. X-raying the Galaxy would open completely new physics.

ROSAT (Röntgensatellit, 1990-1999) all sky survey

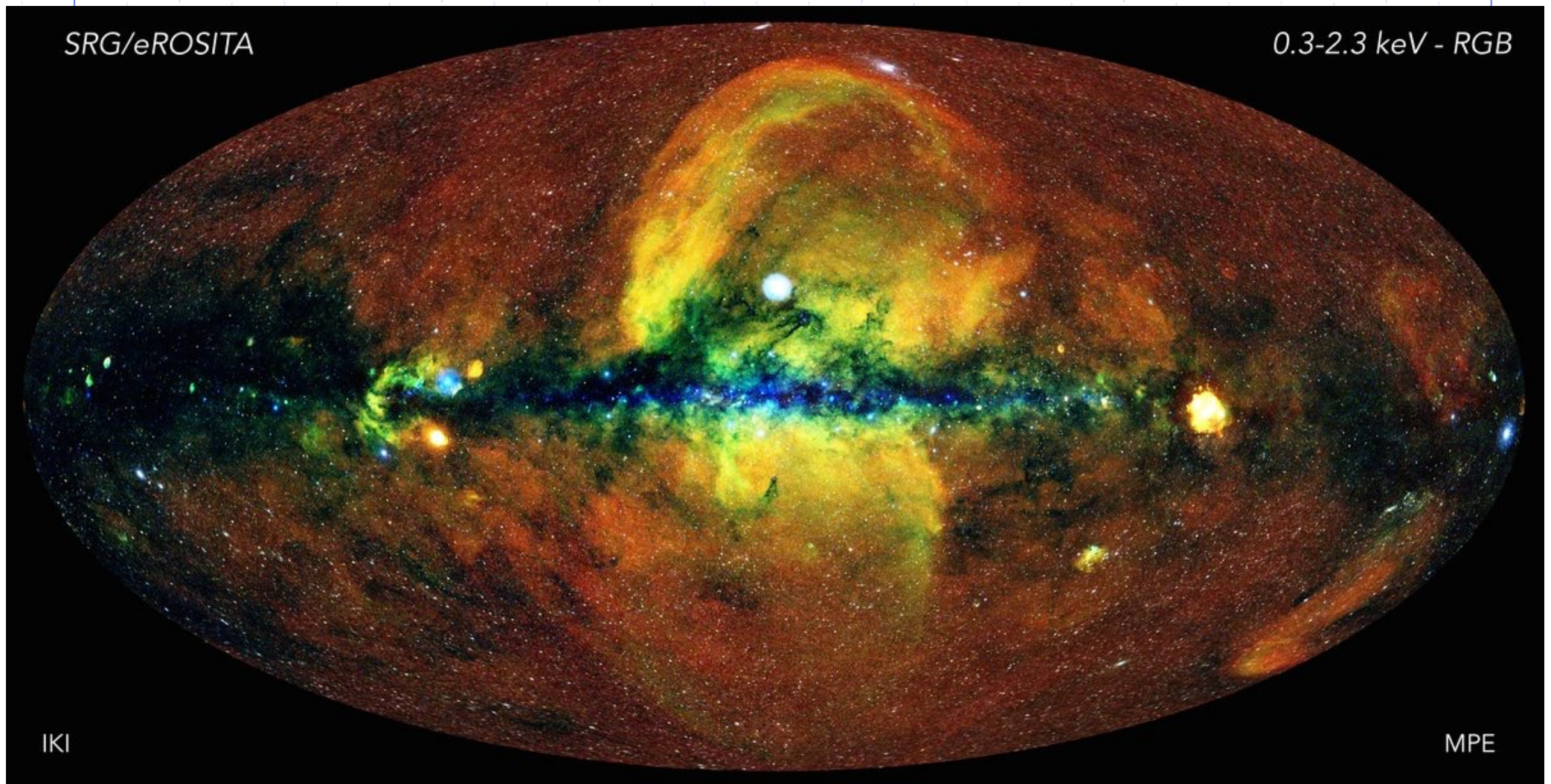


RXTE (Rossi X-ray Timing Explorer, 1995-2012) all sky survey

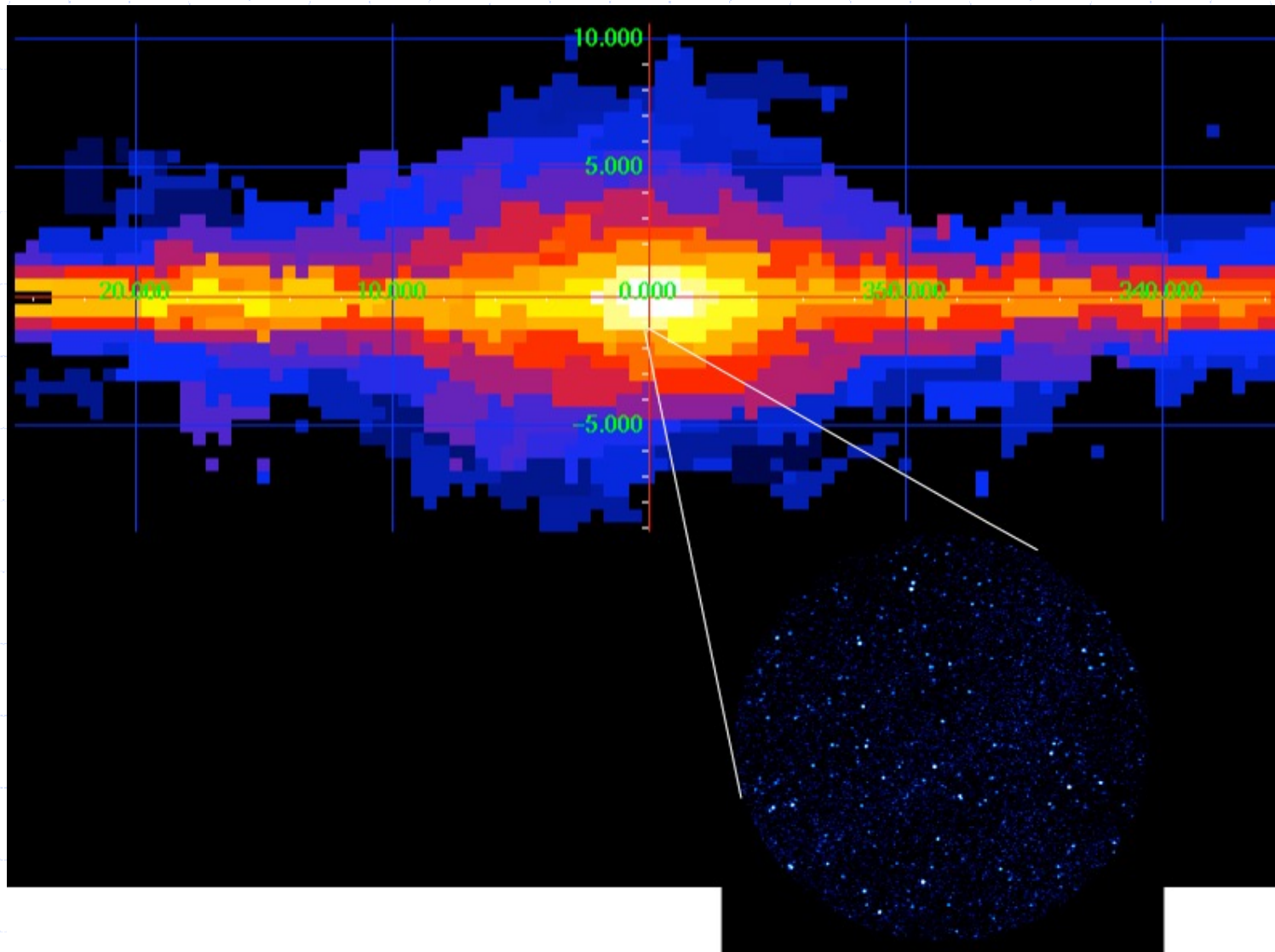




eROSITA/*SRG* (2019-) all sky survey



Galactic ridge “diffuse” X-ray emission



“Diffuse” emission has been a puzzle for many years. It is too hot to be confined by the gravity of the Galaxy. *Chandra* satellite resolved it into point sources: accreting white dwarfs and active stars

X-rays from the Sun as seen by *Yohkoh*

**Corona & several
active regions
are visible.**

**Coronal luminosity:
 $\sim 10^{26}$ erg/s**

**Stellar coronae are
the most numerous
sources of X-rays
in the Milky Way**



White dwarfs

- ◆ 1914: Adams shows that Sirius B has $M \sim 1M_{\odot}$, $T \sim 8000$ K, $R \sim 10,000$ km
- ◆ 1925: Adams confirmed M & R by measuring gravitational redshift -- $z \sim GM/(R c^2) = 0.0003$.
- ◆ 1926: Fermi-Dirac statistics discovered. Fowler applied it to model WDs.
- ◆ 1930: Subramanyan Chandrasekhar: WD model including relativity; mass limit.
- ◆ 1983: Nobel prize to Chandrasekhar "*for his theoretical studies of the physical processes of importance to the structure and evolution of the stars*".

White dwarf

- ◆ Remnant of a solar type star; composed of He, C, O.
- ◆ $M \sim 0.5 M_{\odot}$, $R \sim 10\,000 \text{ km}$, density of 10^6 gram/cc

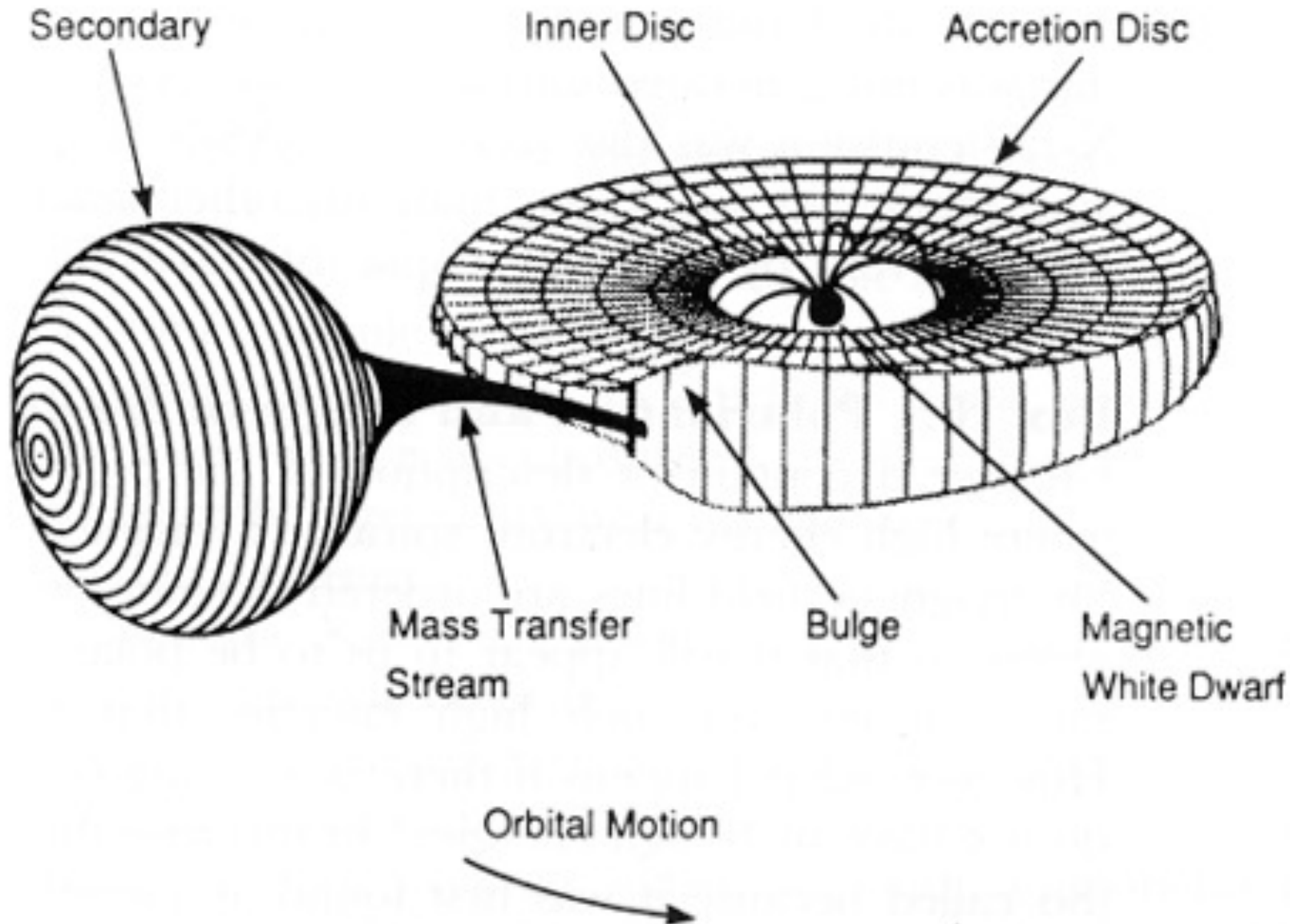


$$M \approx 1.0 M_{\text{sun}}$$

$$R \approx 5800 \text{ km}$$

$$V_{\text{esc}} \approx 0.02c$$

WDs: cataclysmic variables, intermediate polars, polars



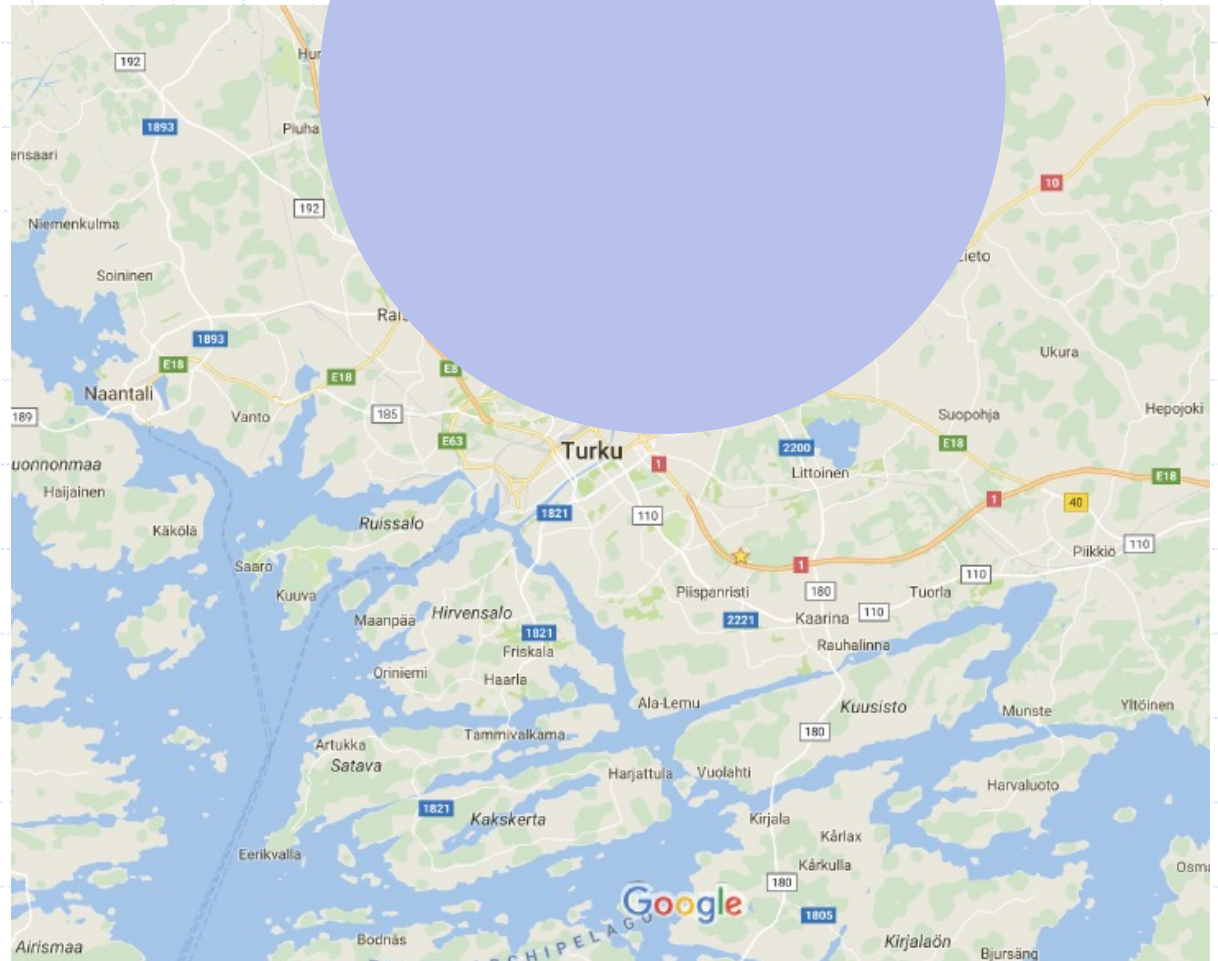
X-ray sources in the Milky Way

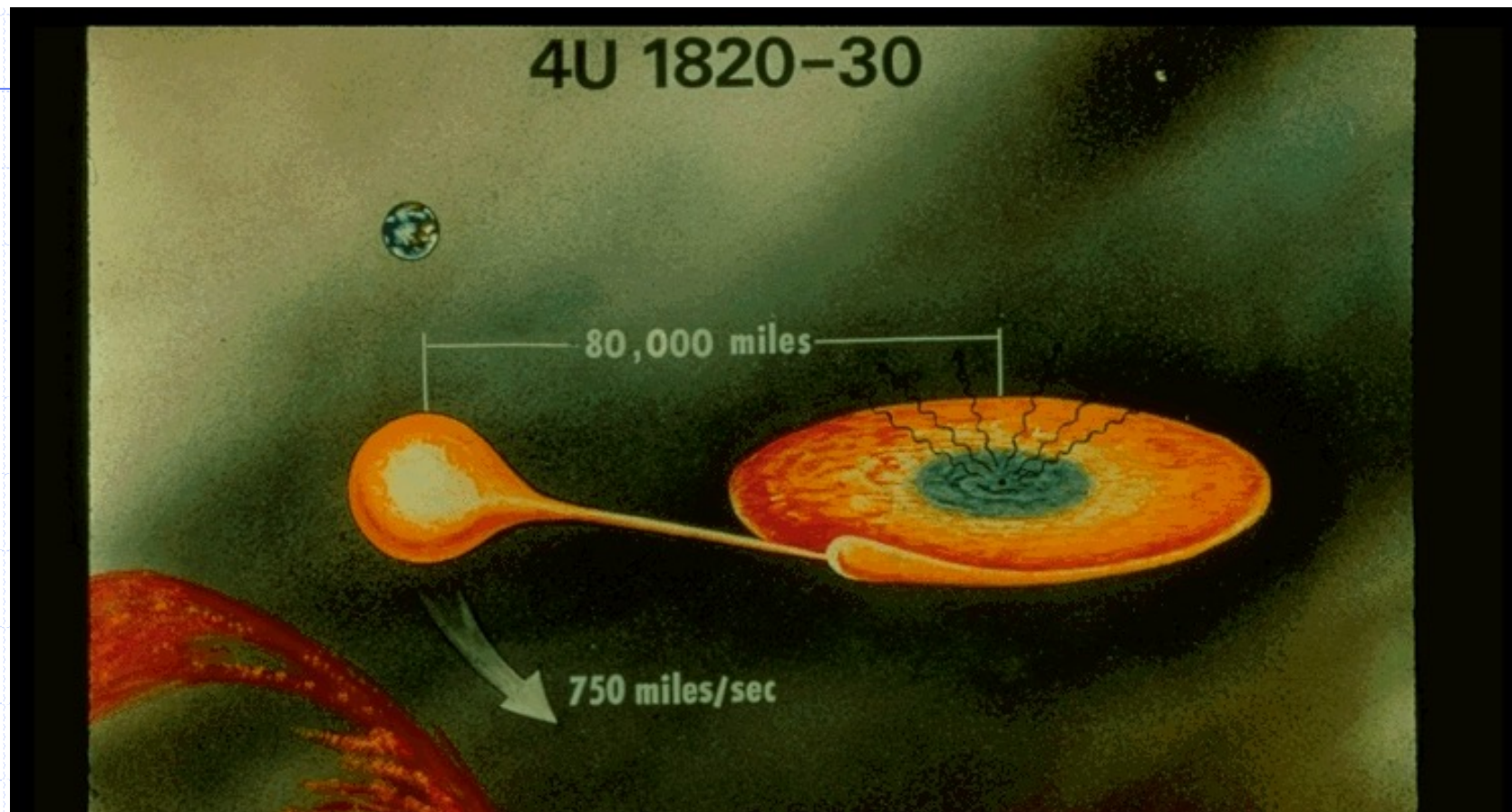
- ◆ The most numerous X-ray emitting sources are active stars and accreting white dwarfs.
- ◆ But what are the brightest X-ray objects? Accreting neutron stars and black holes.

Neutron star

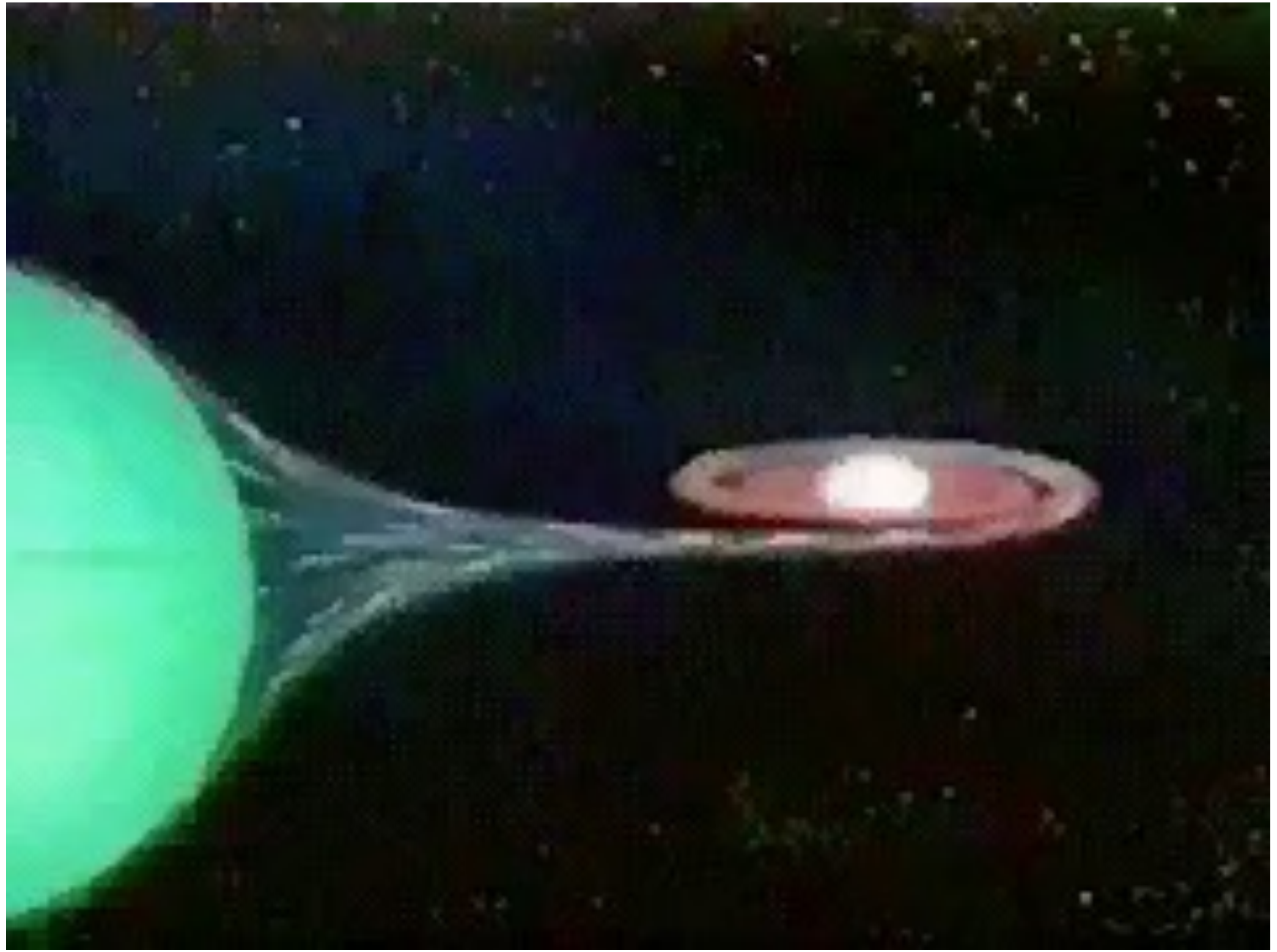
- ◆ Remnant of a massive star composed mainly of neutrons
- ◆ Radius of 11-13 km
- ◆ Mass is about 1.5 Solar masses
- ◆ Dense (10^{15} gram/cc = Mount Everest / liter)
- ◆ Magnetic field is 10^8 - 10^{15} times stronger than the Sun's
- ◆ Rotation period from 1.5 ms to a few 1000 s.

Neutron star vs. Turku





1. Some neutron stars are part of binary systems (low- or high- mass X-ray binaries) Here the companion low-mass star is supplying gas to a neutron star via Roche-lobe overflow.
2. X-ray binaries are some of the most luminous X-ray sources in the Galaxy; Some of these have luminosity close to 10^{38} erg/s or the Eddington limit.
3. The luminosity is generated by a combination of emission from the accretion disc and thermal emission from hot gas accreted by the neutron star (nuclear reactions provide ~ 10 times less energy than potential energy release when the compact object is a neutron star).



◆ A compact object in a binary system

- Tidal forces can rip matter of the other star
- Matter goes into orbit around compact object – forms an **accretion disc**
- As matter flows in towards the compact object, it gives up huge amount of energy.
- The accretion efficiency can be estimated as

$$E \approx \frac{GMm}{R} \Rightarrow \eta_{acc} = \frac{E}{mc^2} = \frac{GM}{Rc^2} = \frac{R_s}{2R}$$

Schwarzschild radius

$$R_s = \frac{2GM}{c^2} = 2.95 \text{ km} \left(\frac{M}{M_\odot} \right)$$

◆ Accretion efficiency:

- For a white dwarf ($M \sim 0.5 M_{\odot}$, $R \sim 10\,000 \text{ km}$)

$$\eta_{acc,WD} = \frac{GM}{Rc^2} = 7 \times 10^{-5}$$

- For a neutron star ($M \sim 1.5 M_{\odot}$, $R \sim 15 \text{ km}$)

$$\eta_{acc,NS} = \frac{R_s}{2R} = \frac{3 \text{ km} \times 1.5}{2 \times 15 \text{ km}} = 0.15$$

- Compare this to efficiency of thermonuclear reactions that power stars

$$\eta_{nuclear}(4\text{H} \rightarrow \text{He}) \approx \frac{4m_{\text{H}} - m_{\text{He}}}{4m_{\text{H}}} \approx 7 \times 10^{-3}$$

◆ Accretion velocity and virial temperature

$$\frac{mV^2}{2} \approx kT_{\text{vir}} \approx \frac{GMm}{R} \Rightarrow V = \sqrt{\frac{2GM}{R}} = c\sqrt{\frac{R_s}{R}}, \quad T_{\text{vir}} \approx \frac{GMm_p}{kR}$$

- For a white dwarf ($M \sim 0.5M_{\odot}$, $R \sim 10\,000\text{km}$)

$$V = 3.6 \times 10^8 \text{ cm/s} = 3.6 \times 10^3 \text{ km/s} \approx 0.02c$$

$$T_{\text{vir}} \approx 0.8 \times 10^9 \text{ K} \approx 70 \text{ keV}$$

- For a neutron star ($M \sim 1.5 M_{\odot}$, $R \sim 15 \text{ km}$)

$$V = 1.4 \times 10^{10} \text{ cm/s} = 1.4 \times 10^5 \text{ km/s} \approx c/2$$

$$T_{\text{vir}} = 1.6 \times 10^{12} \text{ K} = 140 \text{ MeV}$$

- ◆ Radiation is emitted at a surface of a compact object.
- ◆ Maximum photon energy (corresponding to the maximum gas temperature) $h\nu = kT_{\text{vir}}$
- ◆ Minimum photon energy can be estimated from the Stefan-Boltzmann law.

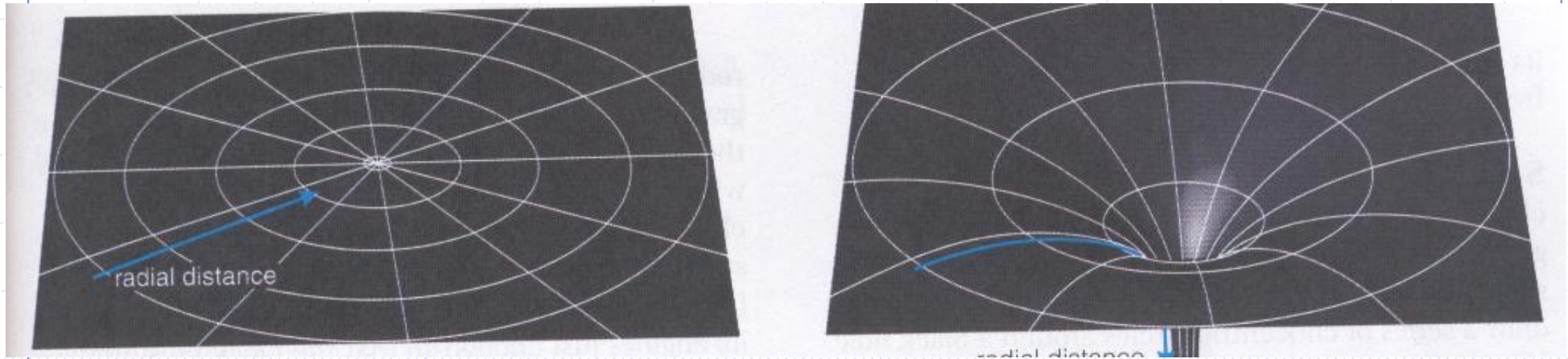
Black body is the most efficient radiator

$$L = 4\pi R^2 \sigma_{SB} T^4$$

For a white dwarf: $T_{\text{min}} \approx 3 \text{ eV}$, $T_{\text{max}} \approx 70 \text{ keV}$

For a neutron star: $T_{\text{min}} \approx 1 \text{ keV}$, $T_{\text{max}} \approx 140 \text{ MeV}$

Black Holes

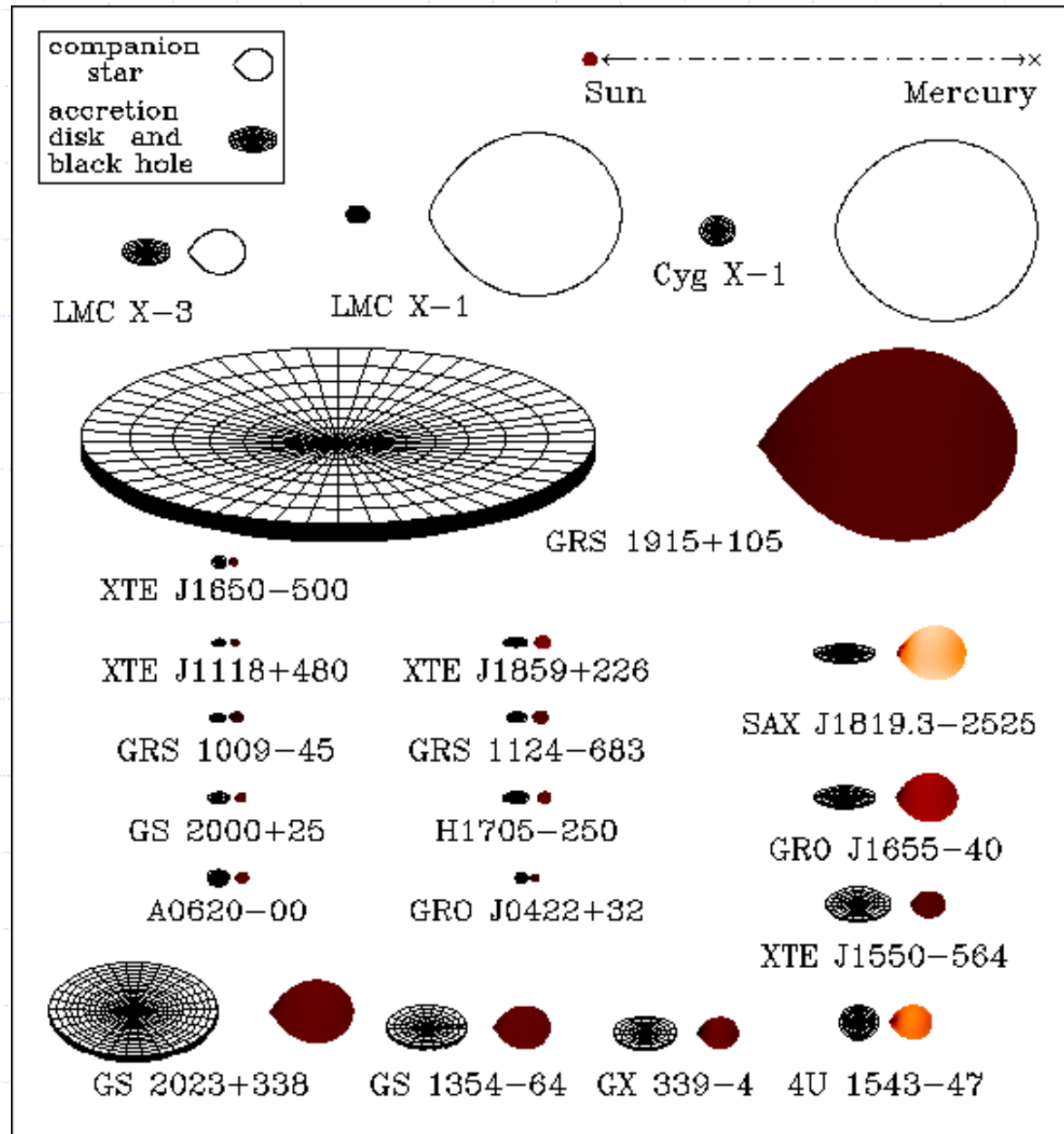


- ◆ Idea of an object with gravity so strong that light cannot escape first suggested by the Reverend John Mitchell in 1783
- ◆ Pierre-Simon Laplace (1798) – “*A luminous star, of the same density as the Earth, and whose diameter should be two hundred and fifty times larger than that of the Sun, would not, in consequence of its attraction, allow any of its rays to arrive at us; it is therefore possible that the largest luminous bodies in the universe may, through this cause, be invisible.*”

Short history of black holes

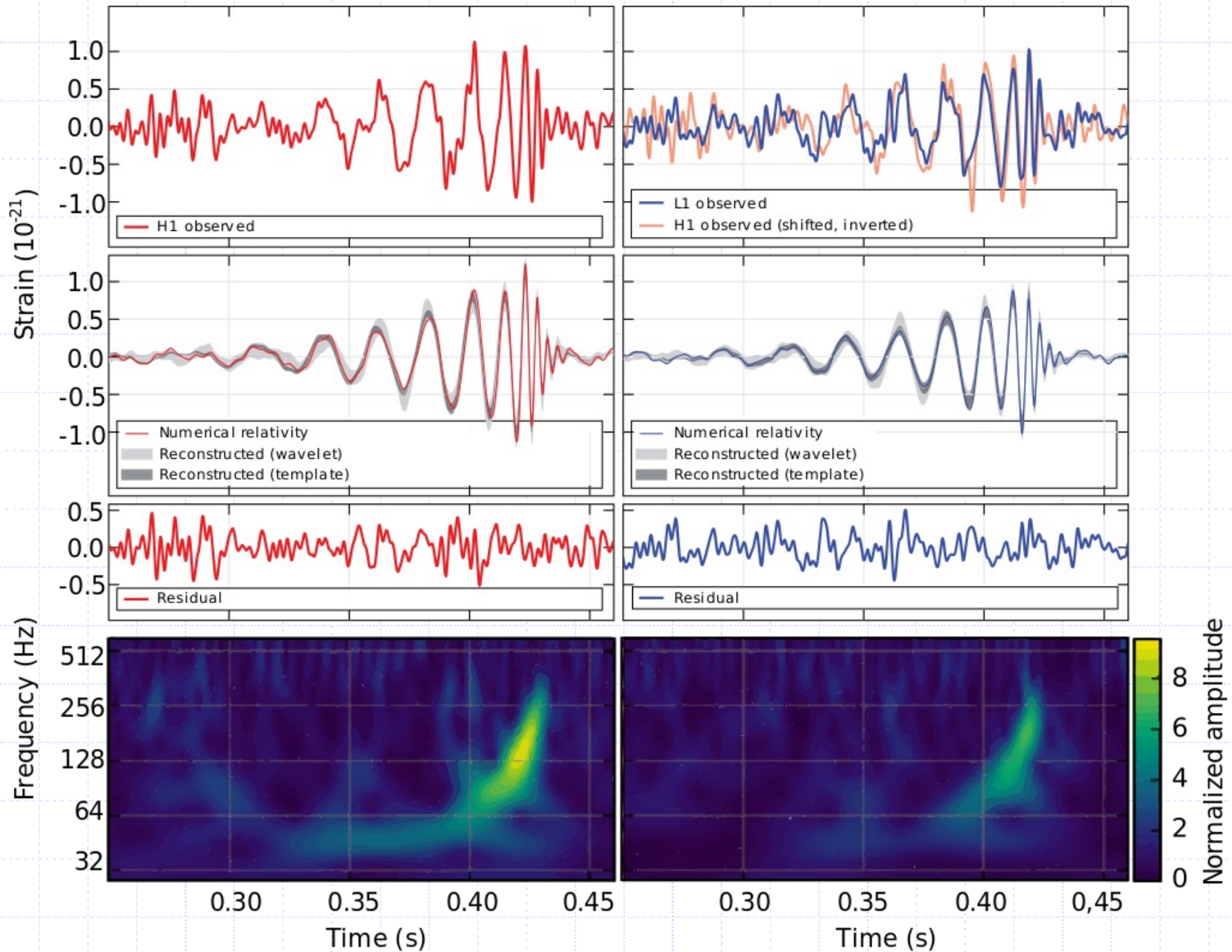
- ◆ 1783: John Mitchell and in 1798 Pierre-Simon Laplace noted the possibility of light not being able to escape
- ◆ 1915: Albert Einstein — theory of general relativity
- ◆ 1916: Karl Schwarzschild — metric for a spherical object
- ◆ 1963: Roy Kerr — metric for a spinning BH
- ◆ 1972: Discovery of Cyg X-1
- ◆ 1995: Miyoshi et al. — mass of BH in NGC 4258 ($4 \times 10^7 M_{\odot}$).
- ◆ 1997: Eckart & Genzel: Sgr A* — a $4 \times 10^6 M_{\odot}$ BH in the Galactic center
- ◆ Masses of a few BHs were measured during merger via gravitational wave signals by LIGO/Virgo (2015-2020)
- ◆ By now about 25 BH have measured masses in the MW (Efficiency of energy production in black hole accretion disks 6% to 42% of the rest mass)
- ◆ 2019/2022: Event Horizon Telescope imaging of M87 and Sgr A*

Black holes in the Milky Way



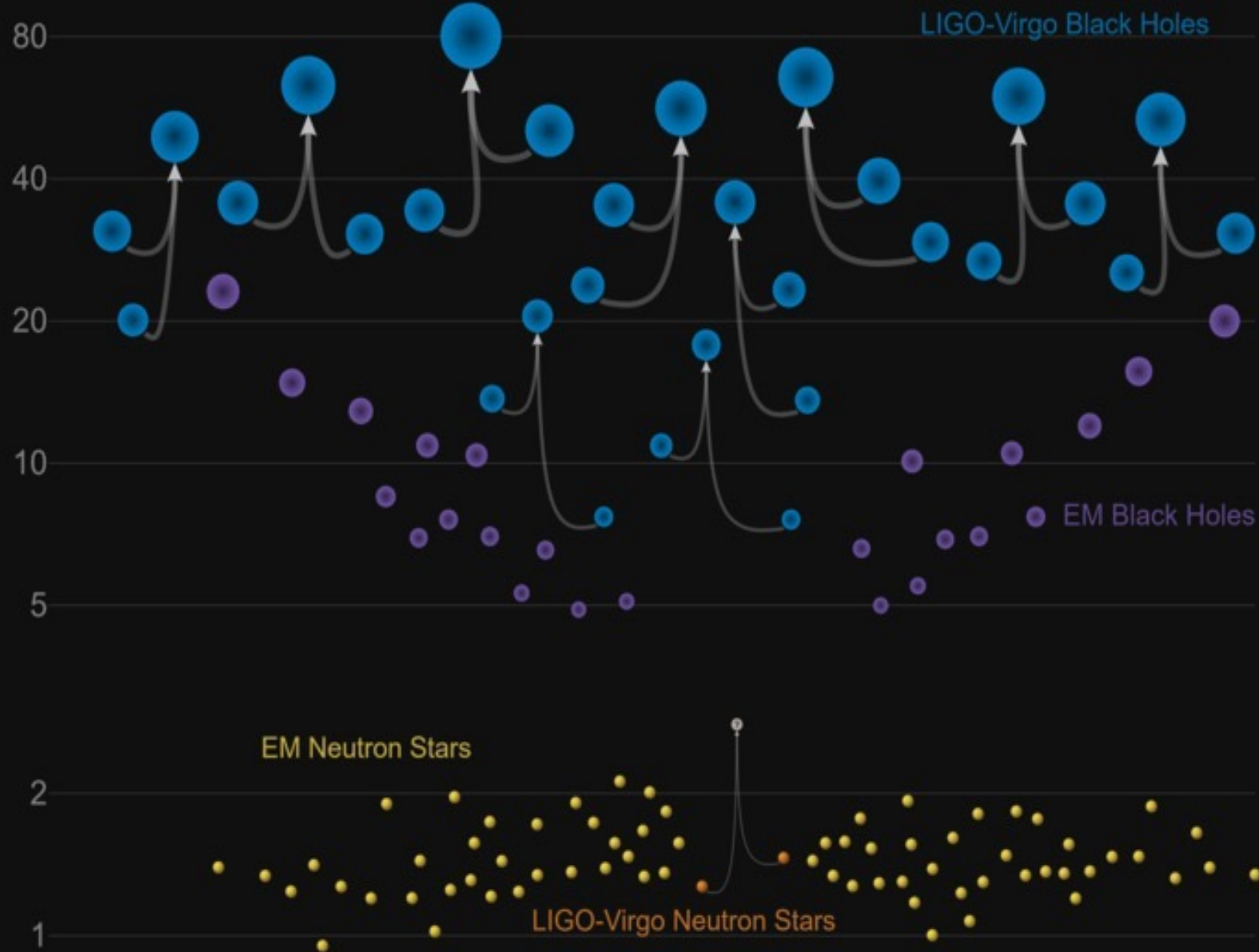
Hanford, Washington (H1)

Livingston, Louisiana (L1)

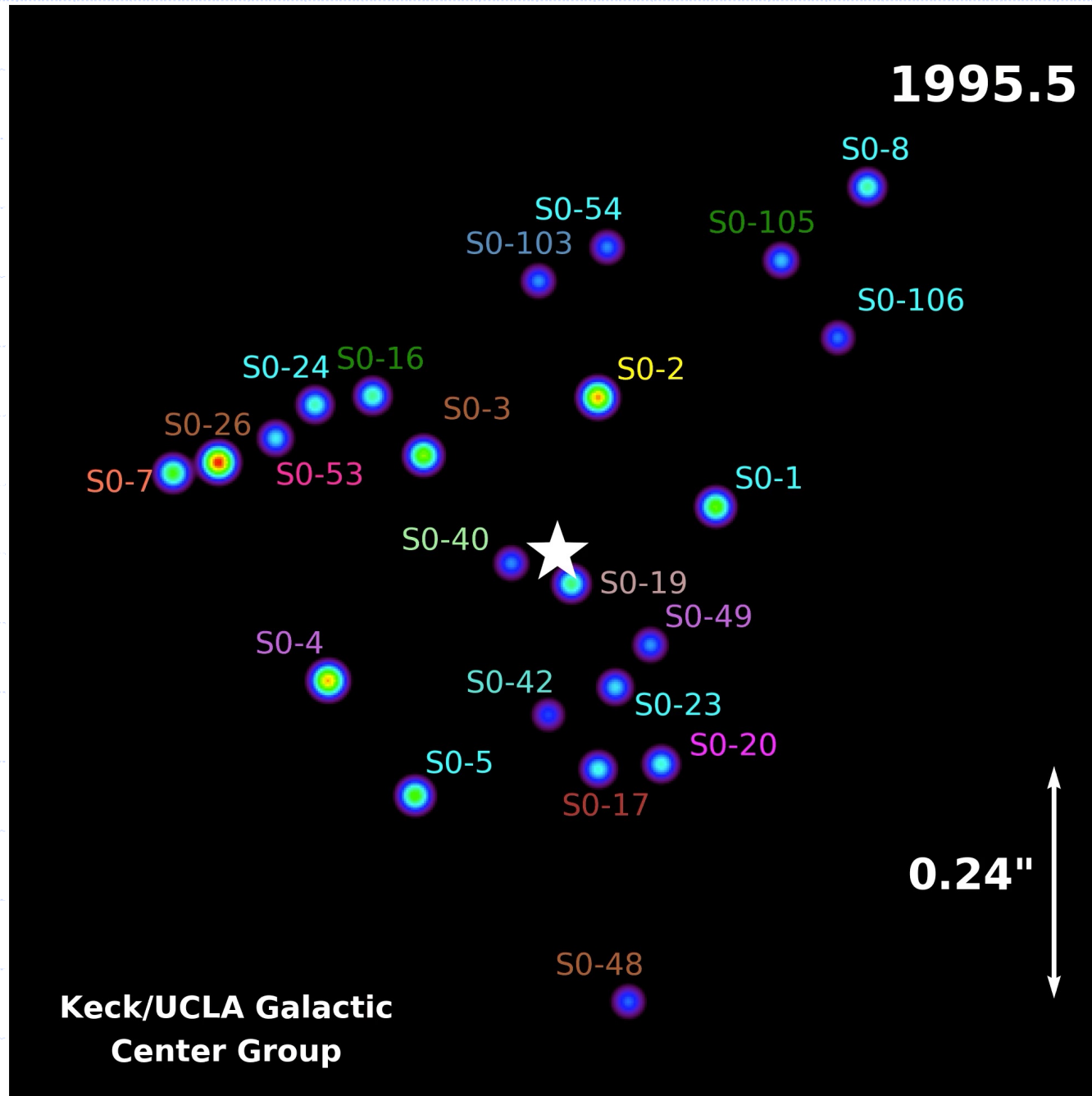


Masses in the Stellar Graveyard

in Solar Masses



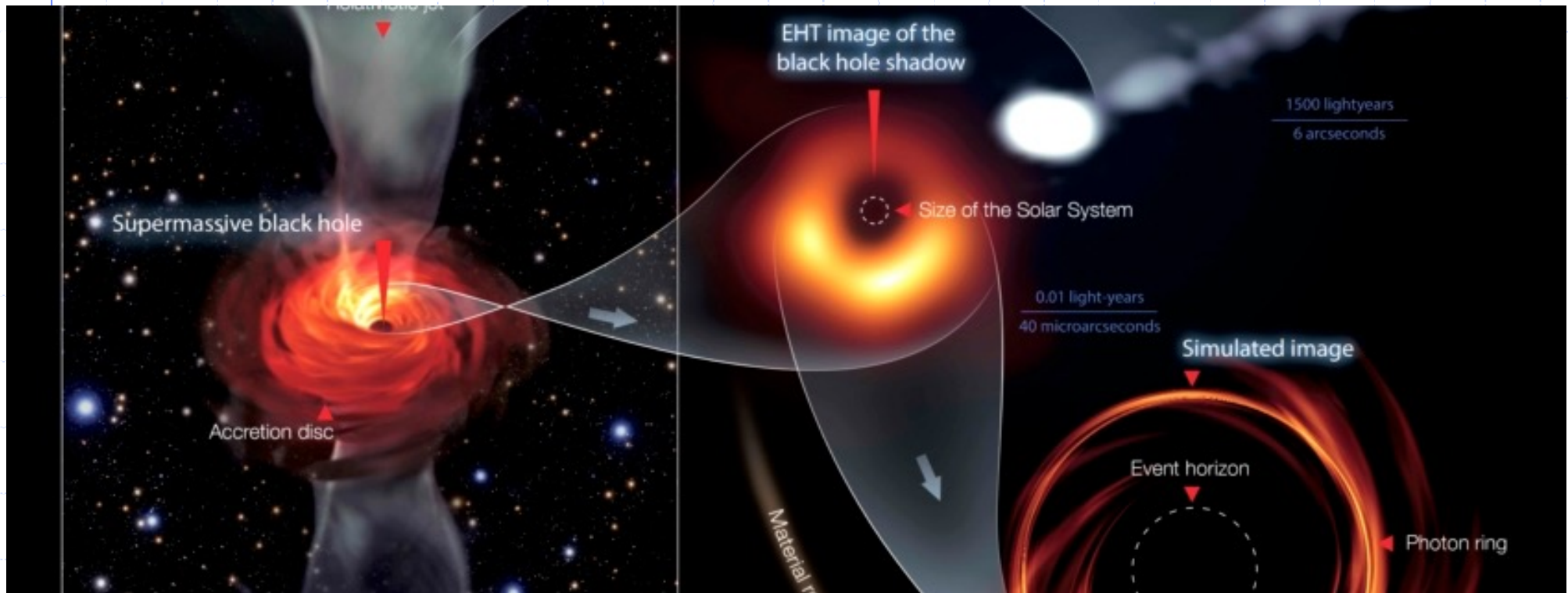
Stellar orbits about the MW center



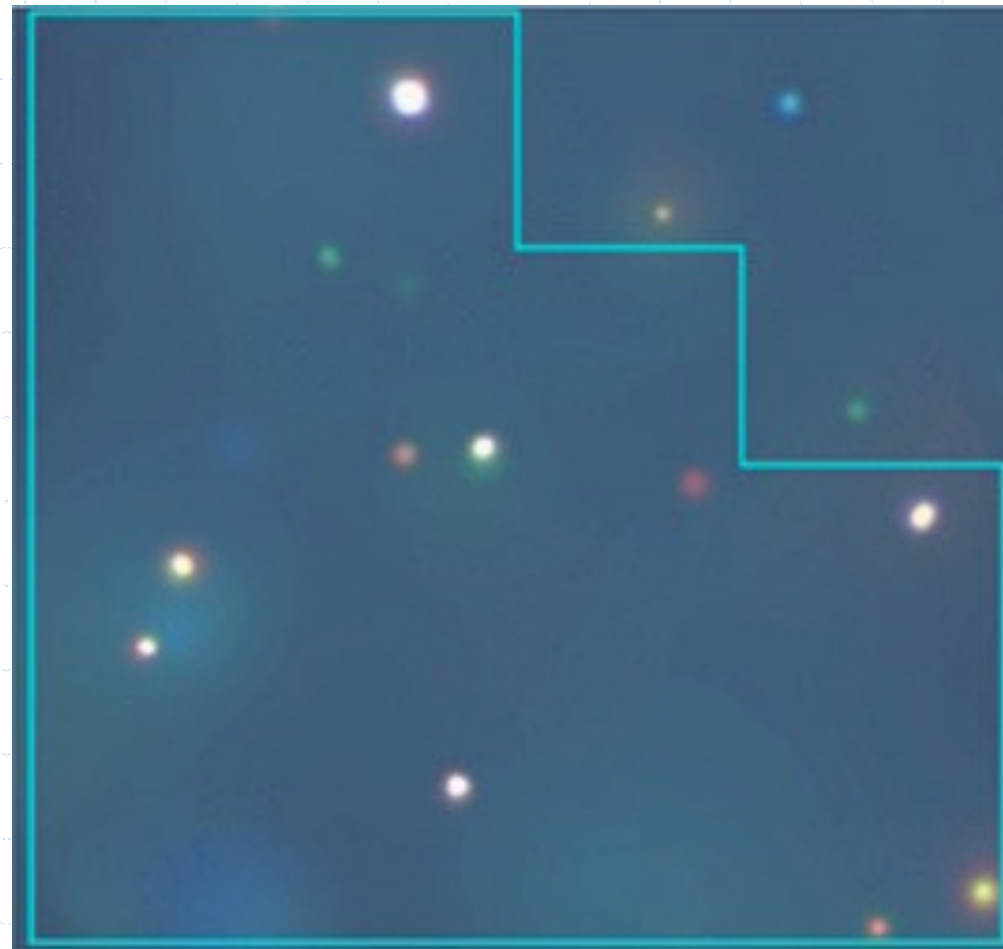
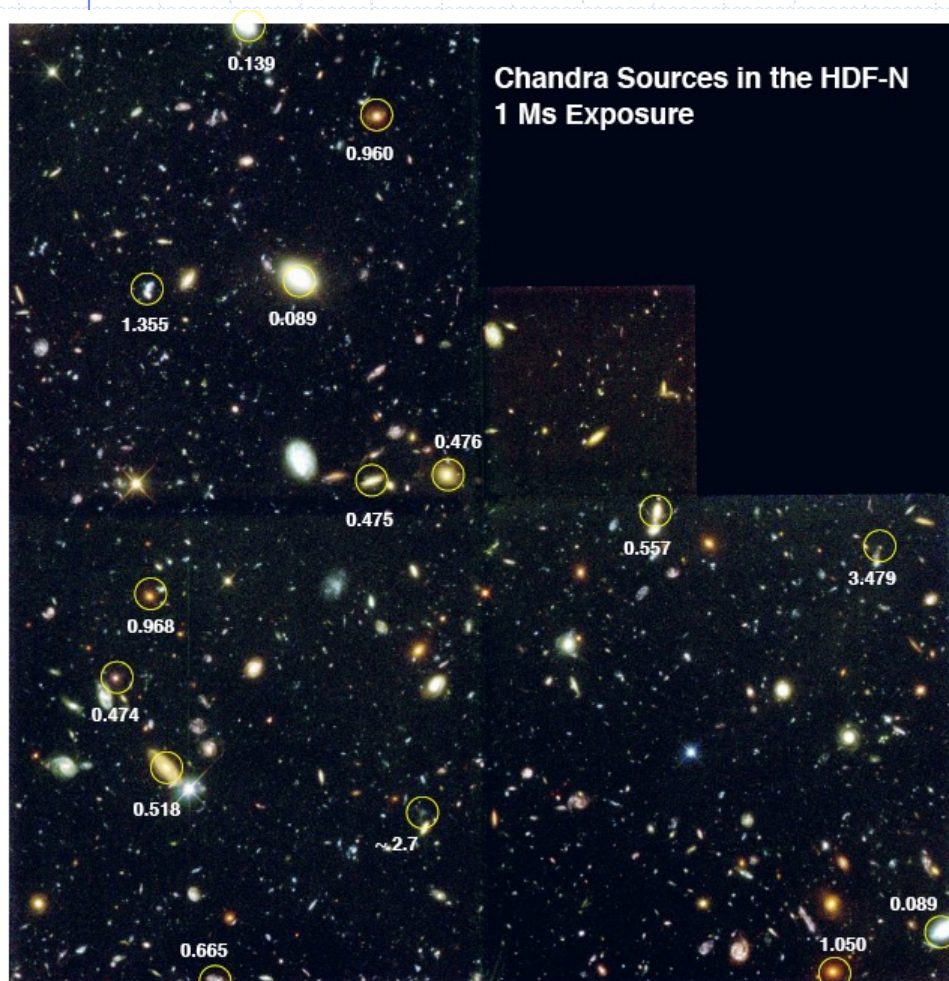
Short history of black holes

- ◆ 2002: Nobel prize in physics to **Riccardo Giacconi** "*for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources*"
- ◆ 2017: Nobel prize in physics to **Rainer Weiss, Barry C. Barish and Kip S. Thorne** "*for decisive contributions to the LIGO detector and the observation of gravitational waves*"
- ◆ 2020: Nobel Prize in Physics to **Roger Penrose** "*for the discovery that black hole formation is a robust prediction of the general theory of relativity*"
- ◆ 2020: Nobel Prize in Physics to **Reinhard Genzel and Andrea Ghez** "*for the discovery of a supermassive compact object at the centre of our galaxy*"

Event Horizon Telescope view of M87



Supermassive black holes in the Hubble deep field



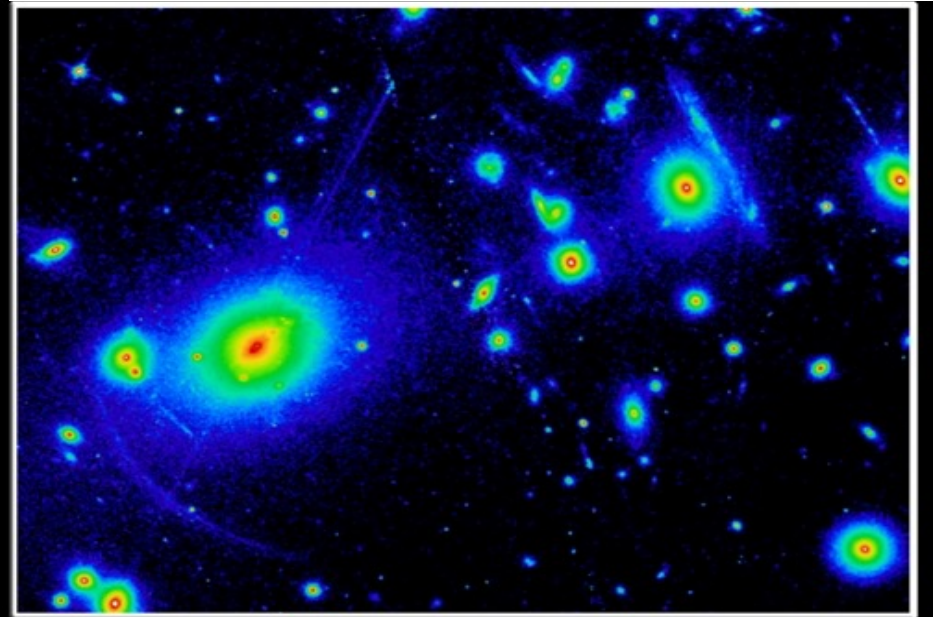
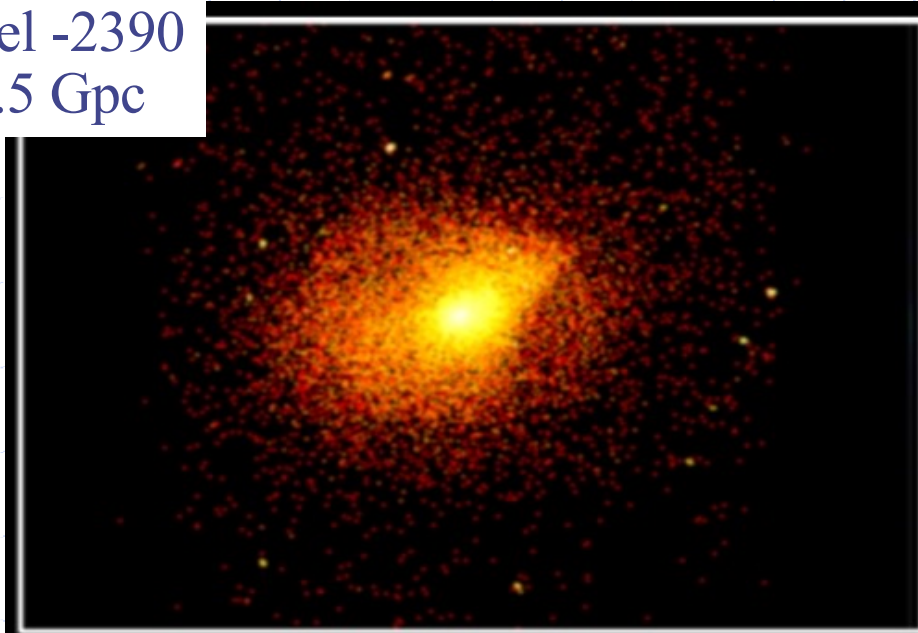
**X-ray point sources:
active galaxies**

X-rays from galaxy clusters

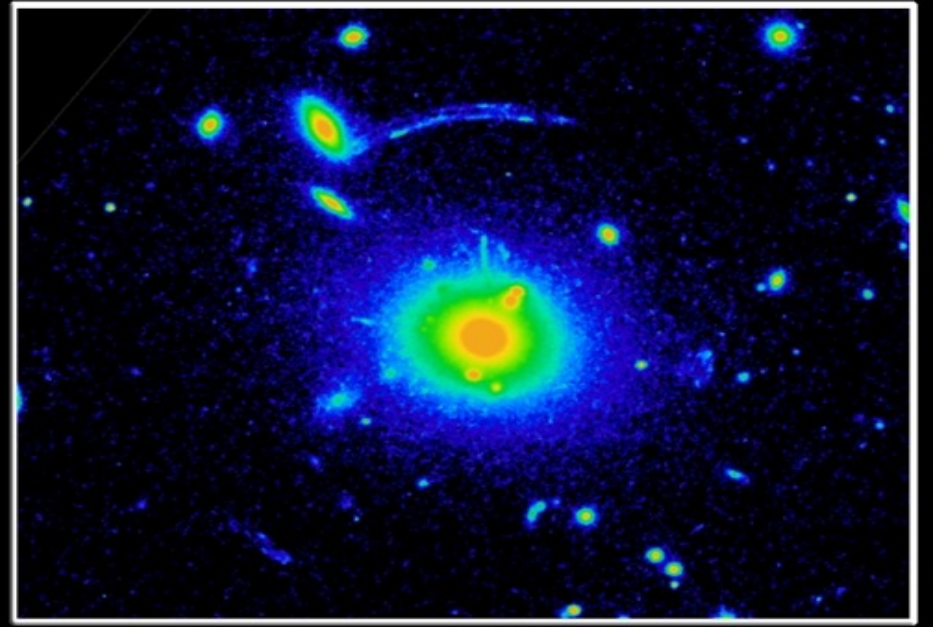
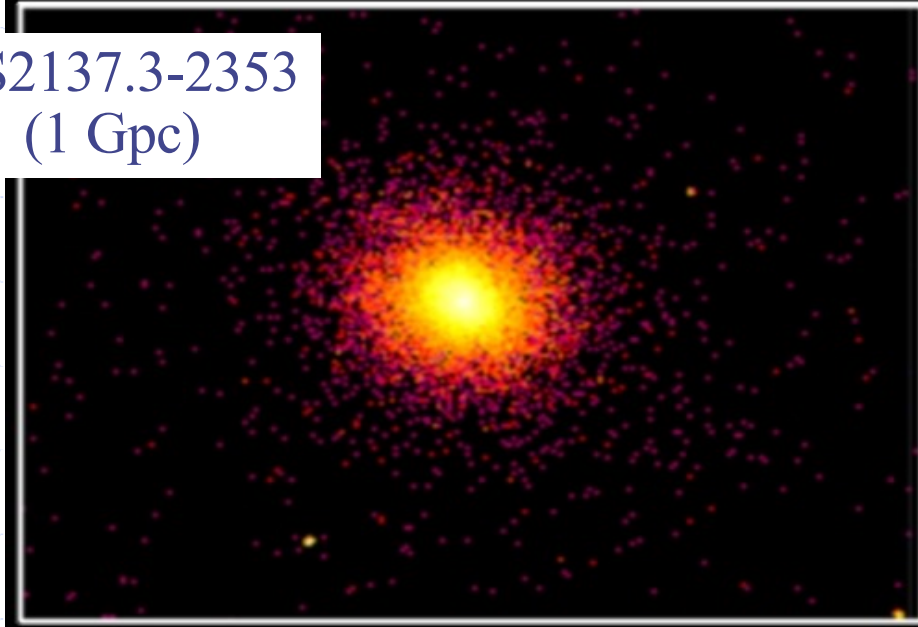
Chandra X-rays; ~ 2 keV

HST - optical image
(note lensing of background galaxies)

Abel -2390
0.5 Gpc



MS2137.3-2353
(1 Gpc)



What have we learned today?

- ❖ That multiwavelength studies are crucial for understanding of astrophysical sources.
- ❖ How the Universe (and the Milky Way) looks at different wavelengths.
- ❖ About penetrating power of the X-rays (as well as radio and gamma-rays).
- ❖ About the distribution of the X-ray sources in the Galaxy: white dwarf binaries, active stars, and X-ray (black hole or neutron star) binaries.
- ❖ We have also learned about accretion efficiency and typical photon energies produced during accretion.
- ❖ About extragalactic X-ray sources: supermassive black holes and clusters of galaxies.
- ❖ About gamma-ray sources: pulsars, SN remnants and active galaxies.