ISAPP 2014: Multi-wavelength and multi-messenger investigation of the visible and dark Universe

High-Energy processes in astronomical sources

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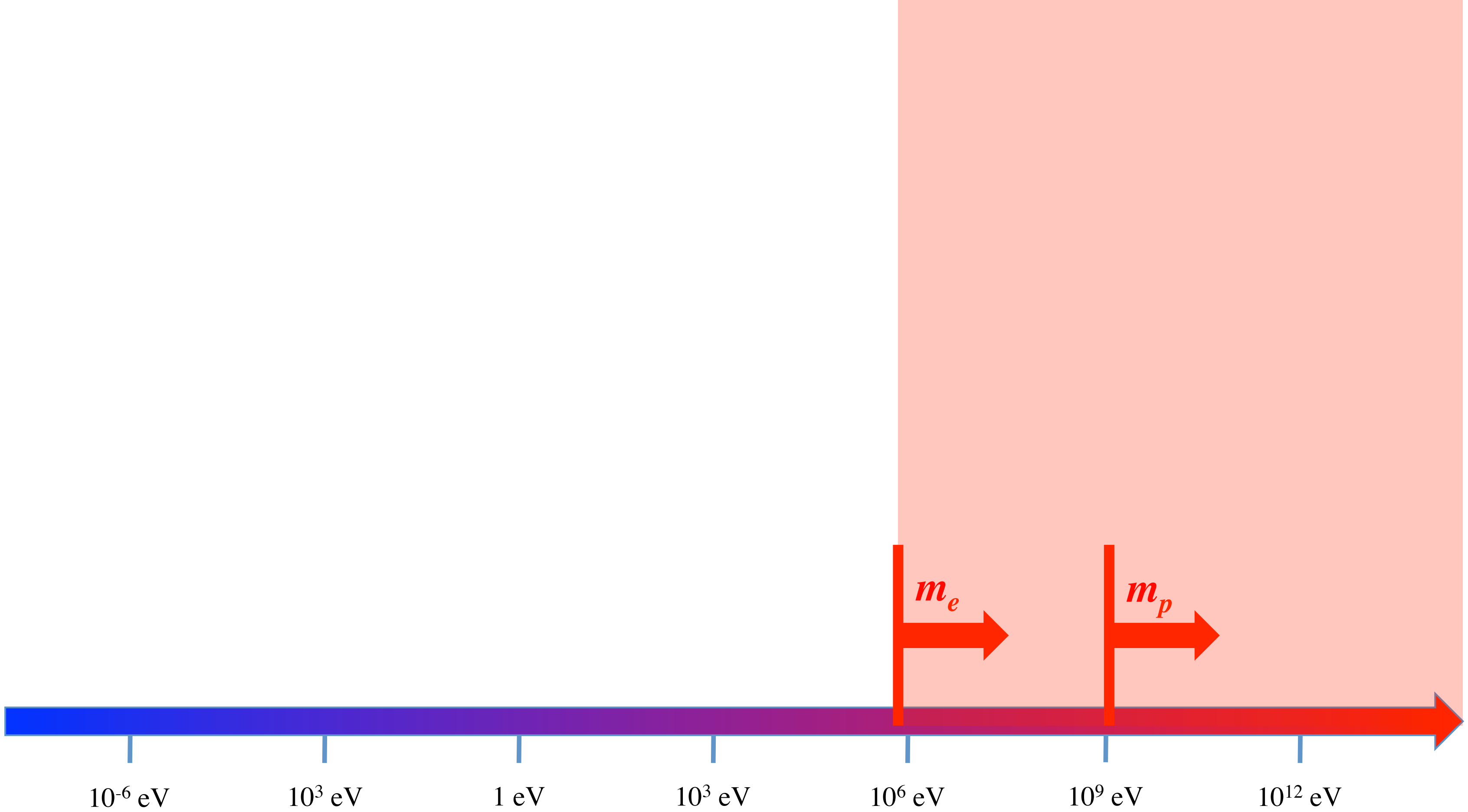
University of Geneva

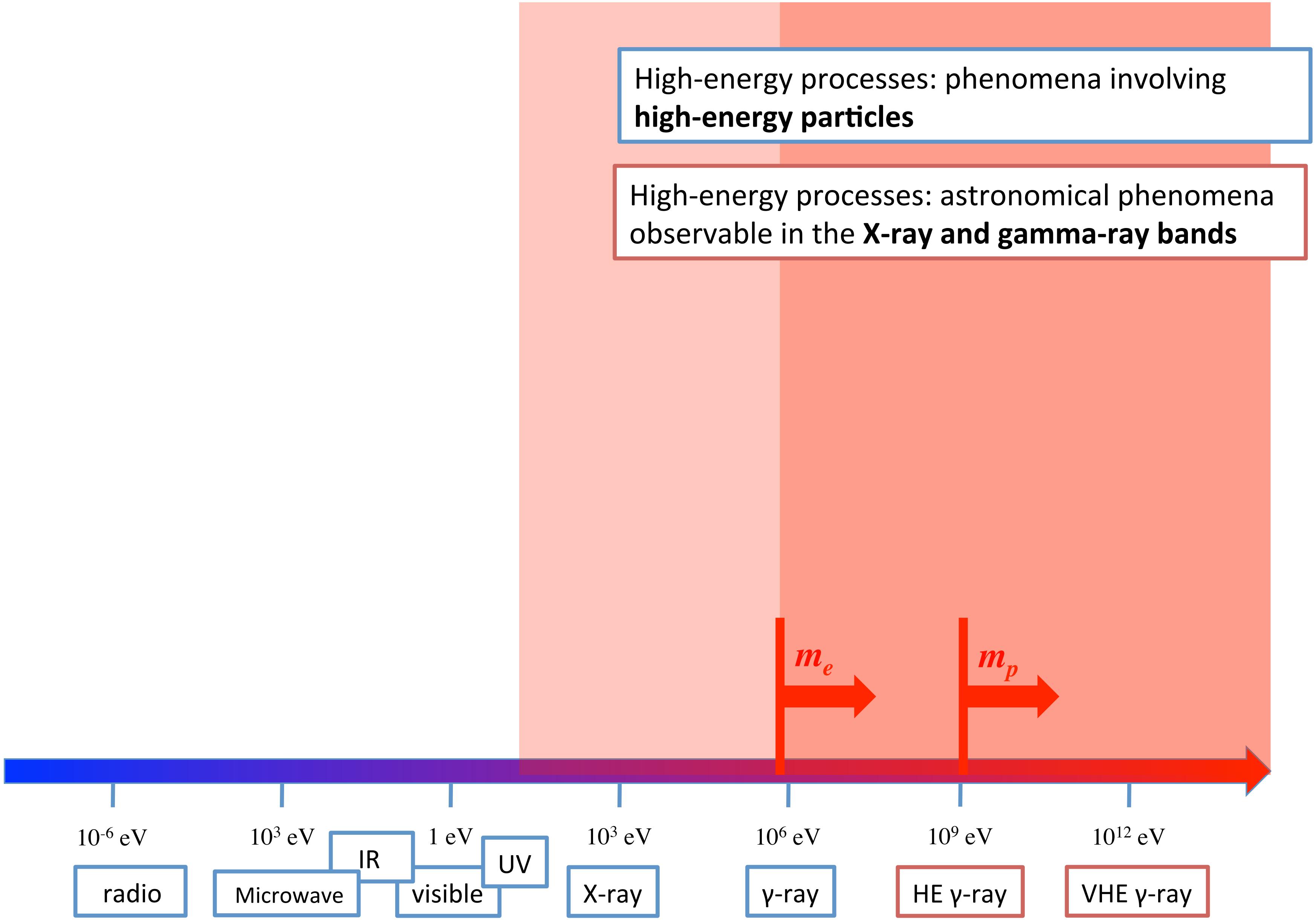
Introduction

High-Energy processes in astronomical sources

High-energy processes: phenomena involving **high-energy particles**



High-Energy processes in astronomical sources

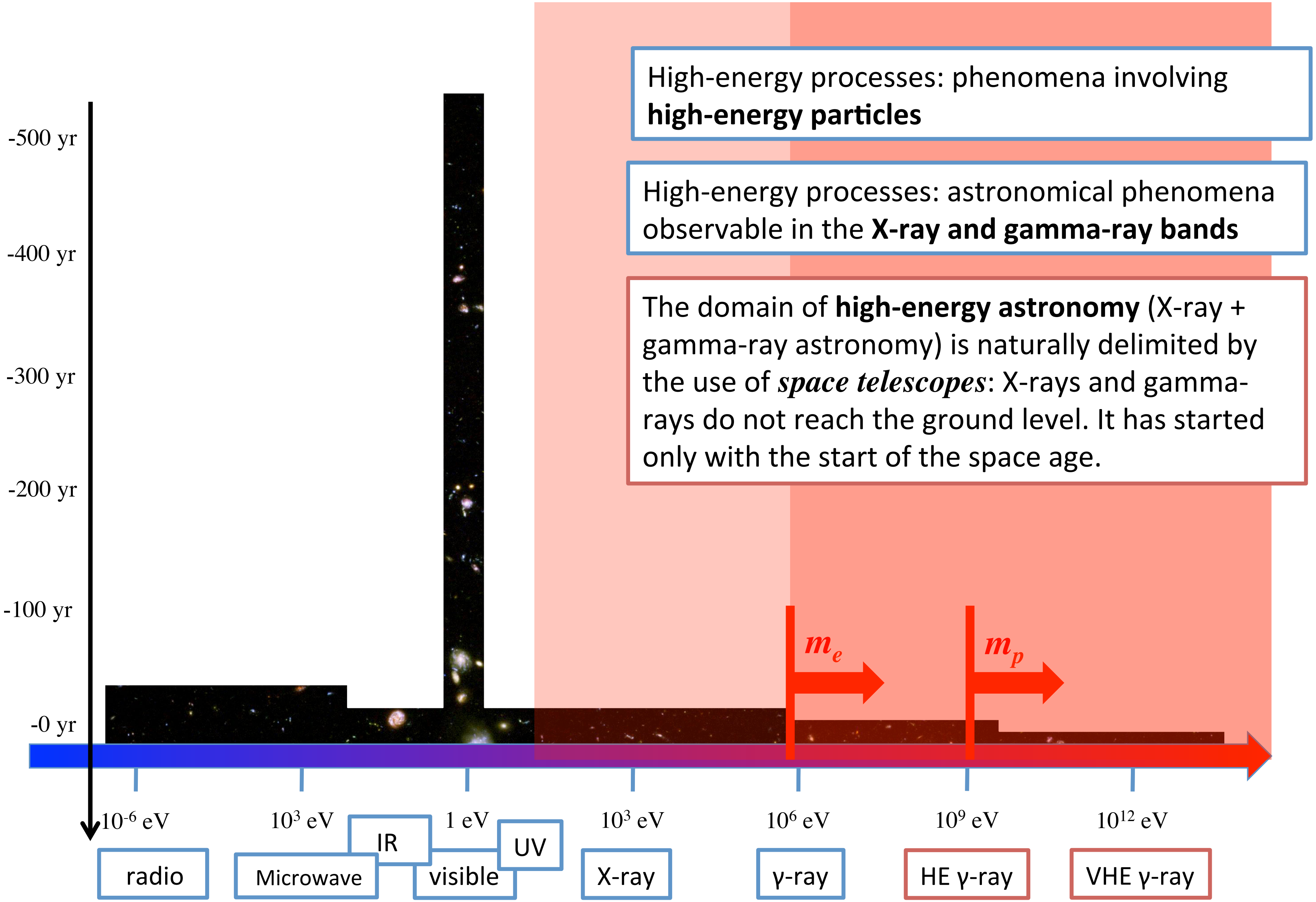


High-Energy processes in astronomical sources

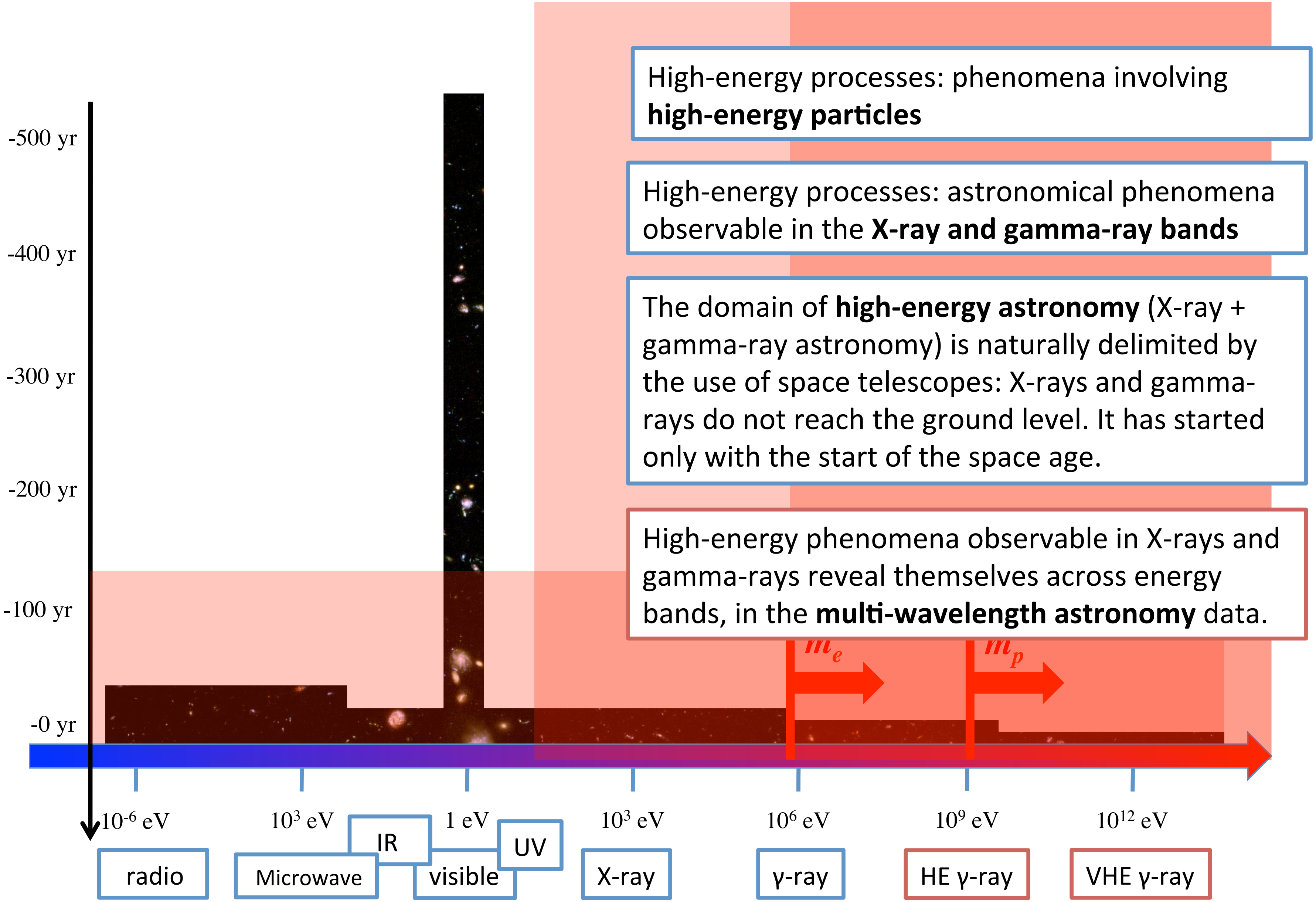
High-energy processes: phenomena involving **high-energy particles**

High-energy processes: astronomical phenomena observable in the **X-ray and gamma-ray bands**

The domain of **high-energy astronomy** (X-ray + gamma-ray astronomy) is naturally delimited by the use of ***space telescopes***: X-rays and gamma-rays do not reach the ground level. It has started only with the start of the space age.

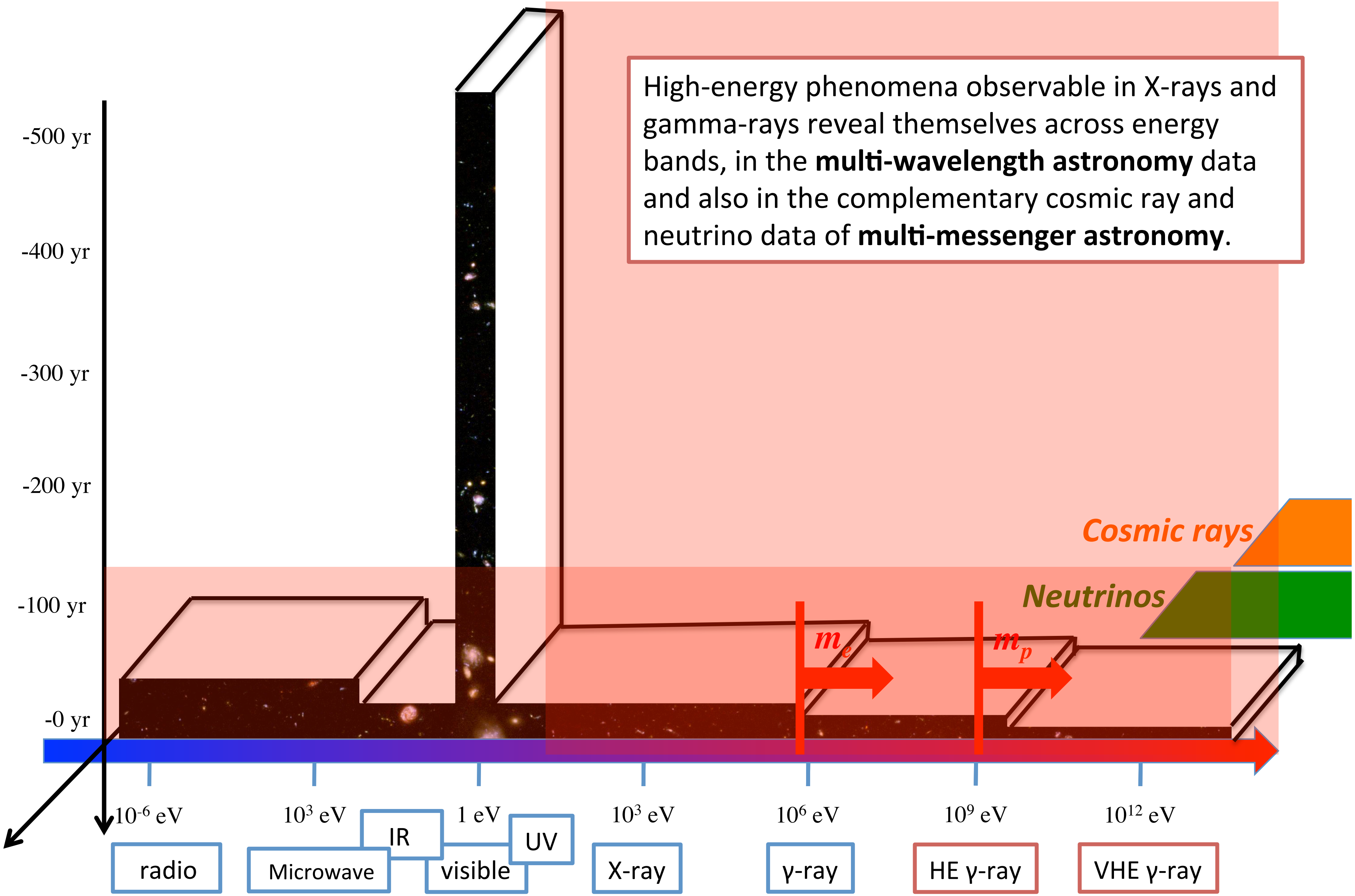


High-Energy processes in astronomical sources

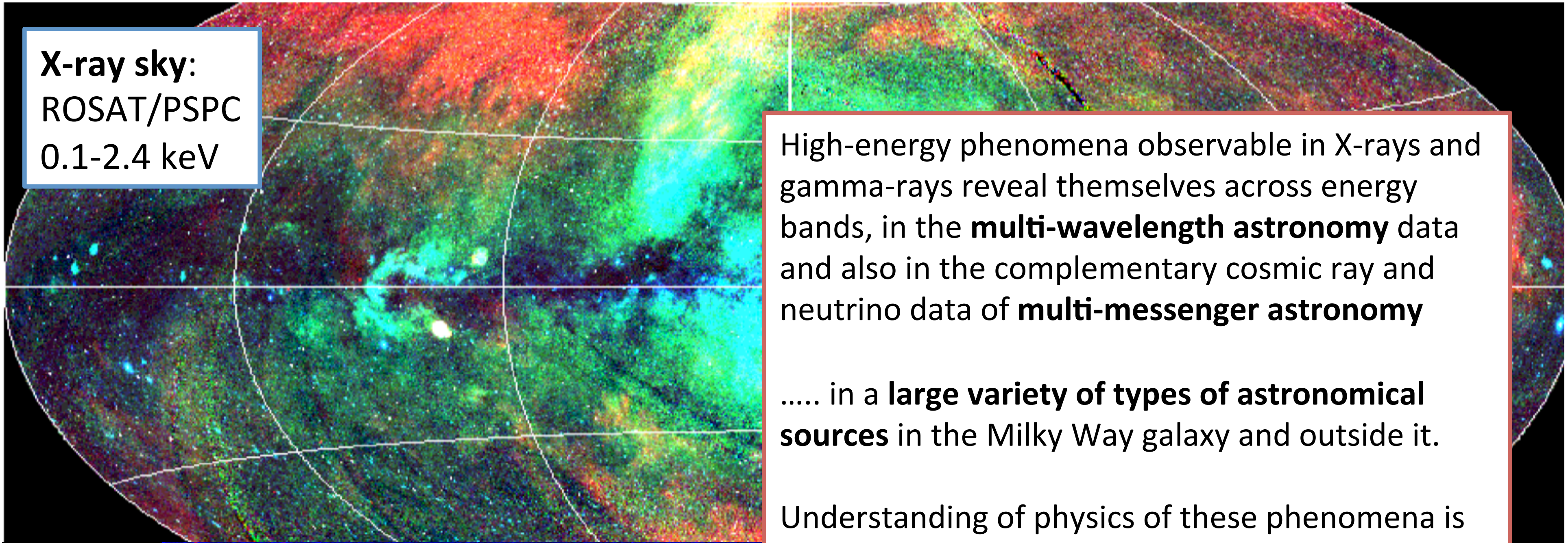


High-Energy processes in astronomical sources

High-energy phenomena observable in X-rays and gamma-rays reveal themselves across energy bands, in the **multi-wavelength astronomy** data and also in the complementary cosmic ray and neutrino data of **multi-messenger astronomy**.



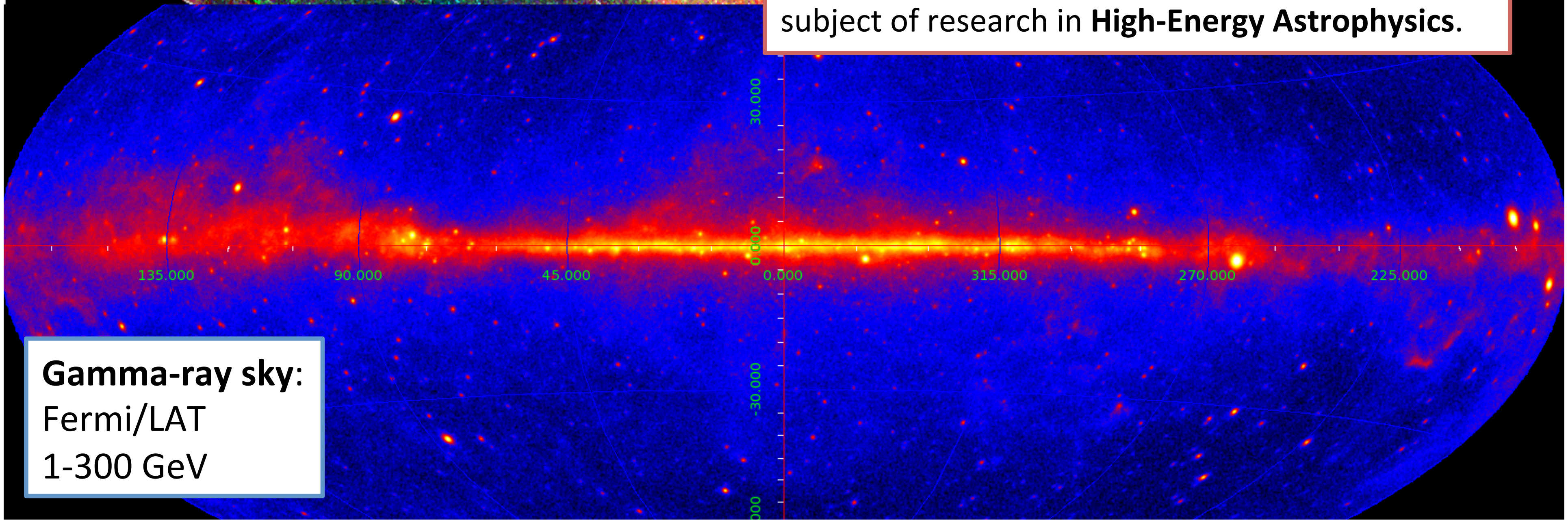
High-Energy processes in astronomical sources



High-energy phenomena observable in X-rays and gamma-rays reveal themselves across energy bands, in the **multi-wavelength astronomy** data and also in the complementary cosmic ray and neutrino data of **multi-messenger astronomy**

….. in a **large variety of types of astronomical sources** in the Milky Way galaxy and outside it.

Understanding of physics of these phenomena is subject of research in **High-Energy Astrophysics**.



High-Energy processes in astronomical sources

The school is dedicated to the multi-messenger and multi-wavelength approach to the indirect search for dark matter in the Universe. The first week of lectures will cover introductory courses on particle physics, particle cosmology and astrophysical processes relevant for dark matter studies. The second week will deal with more advanced courses on the full range of multi-wavelength and multi-messenger signals of dark matter. The courses will cover both the theoretical/phenomenological and experimental/observational aspects, in order to give an exhaustive overview of this complex field. The program will be complemented by a seminar on the current status of gravitational waves physics.

High-Energy processes in astronomical sources
…and indirect search for DM

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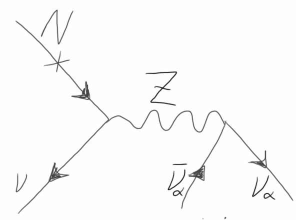
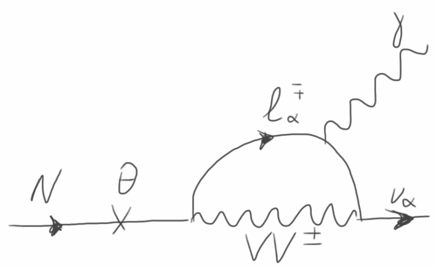
Example 1: Sterile neutrino DM

Sterile neutrinos with masses in the $\sim$1-100 keV range are considered as viable candidates for the DM. They are not detectable in the "direct search" experiments, because the energy transfer in their collisions with ordinary matter particles is tiny (about 1 meV) and not detectable by imaginable experimental setups.

DM sterile neutrinos are unstable particles. Their main decay channel is into three active neutrinos, with the life time much longer than the age of the Universe. The active neutrino decay products are also undetectable.

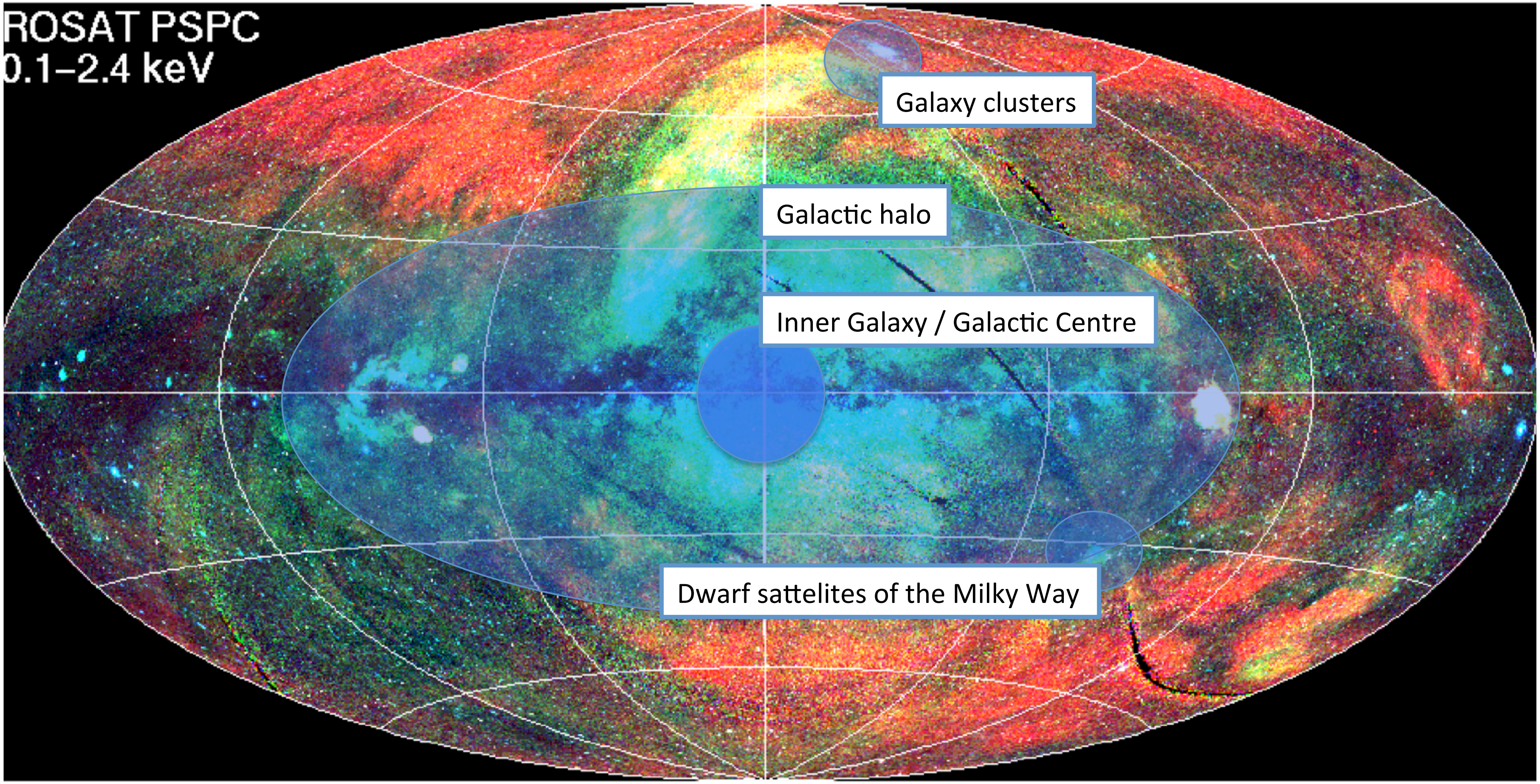


A sub-dominant decay channel is into an active neutrino and a **photon**. The energy of photon is equal to the rest energy of the DM sterile neutrino. It is in the **X-ray range**. Search for the monochromatic X-ray emission from the decays of DM sterile neutrinos in large DM concentrations (**galaxies, galaxy clusters**) is the only way to confirm or disprove the hypothesis of sterile neutrino nature of the DM.



High-Energy processes in astronomical sources
…and indirect search for DM

***Example 1*: Sterile neutrino DM**



Signal (if any) always appears on top of a very strong astrophysical background (foreground).

High-Energy processes in astronomical sources
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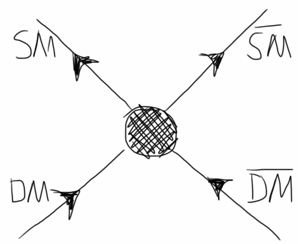
Example 2: gamma-rays from Weakly Interacting Massive Particles (WIMPs)

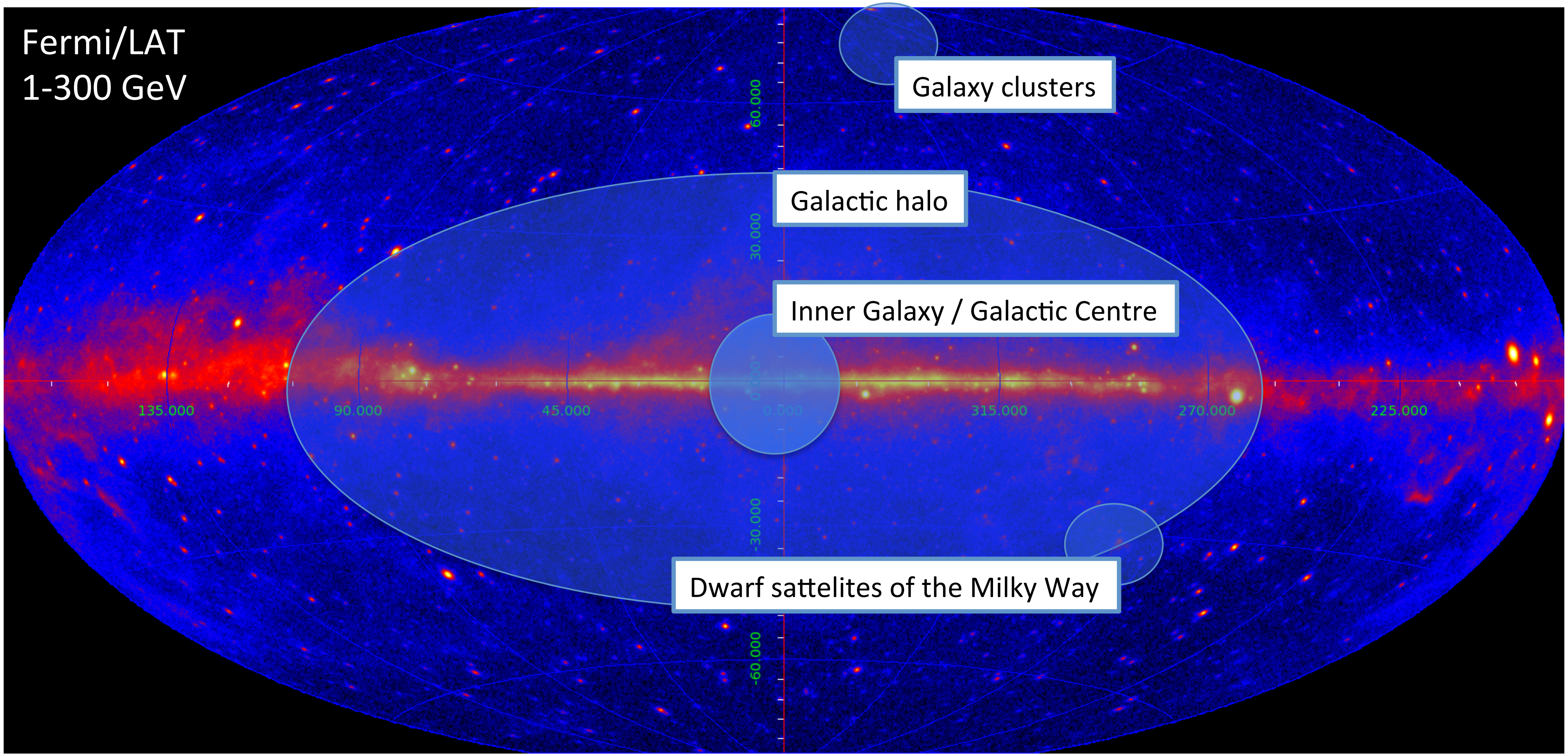
Weakly interacting particles with masses in the ~1-1000 GeV range are considered as viable candidates for the DM. They might be detectable in the “direct search” experiments, but there is no straightforward estimate for the cross-section of their interaction with atomic nuclei composing the laboratory detector.

WIMPs composing the DM halos of galaxies interact with each other, in the same way As they did in the Early Universe. There is a reliable estimate of their interaction cross-section $\sigma v \approx 3\times10^{-26}\ \mathrm{cm^3/s}$. Annihilation of WIMPs into the Standard Model particles results in Production of **gamma-rays**, via several channels. Observations of the gamma-ray flux From the WIMP annihilation in the DM halos of **galaxies and galaxy clusters** provides a complementary test for the hypothesis of the WIMP nature of the DM.



High-Energy processes in astronomical sources
…and indirect search for DM

***Example 2*: gamma-rays from WIMPs**



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***Example 3*: *Charged particles* from WIMPs.**

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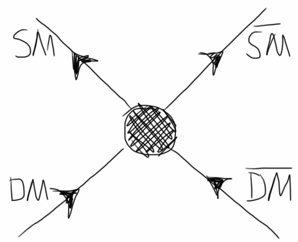
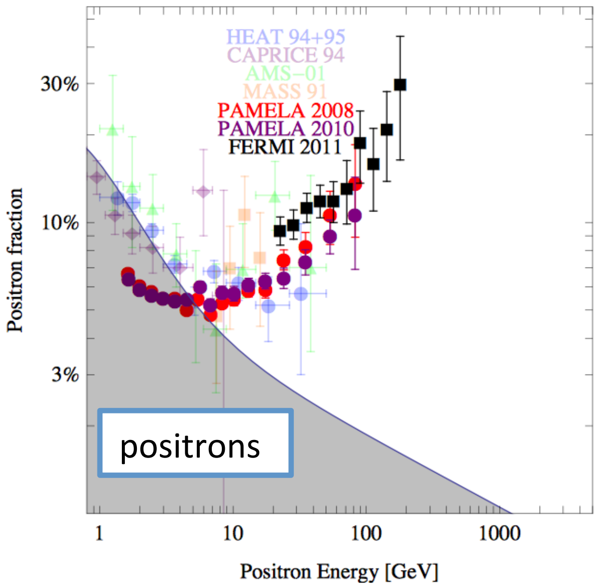
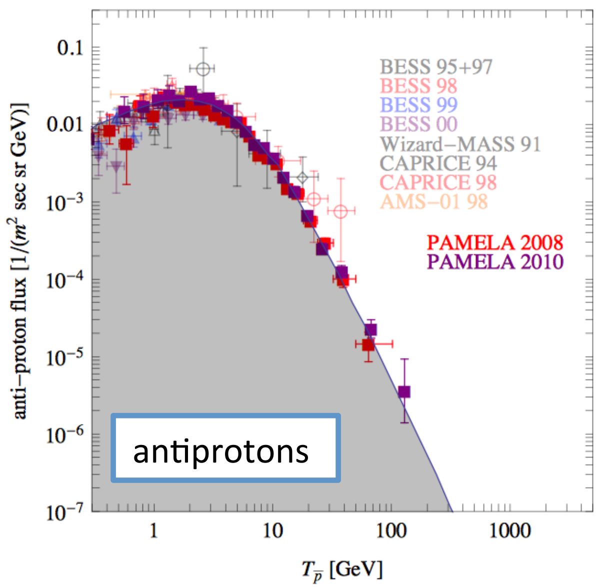
WIMPs composing the DM halos of galaxies interact with each other, in the same way As they did in the Early Universe. There is a reliable estimate of their interaction cross-section $\sigma v \approx 3\times10^{-26}\ \mathrm{cm^3/s}$. Annihilation of WIMPs into the Standard Model particles results in production of charged particles (**protons, antiprotons, electrons, positrons**), via several channels. Detection of the flux of charged particles from the WIMP annihilation in the local **interstellar medium** provides still another complementary test for the hypothesis of the WIMP nature of the DM.

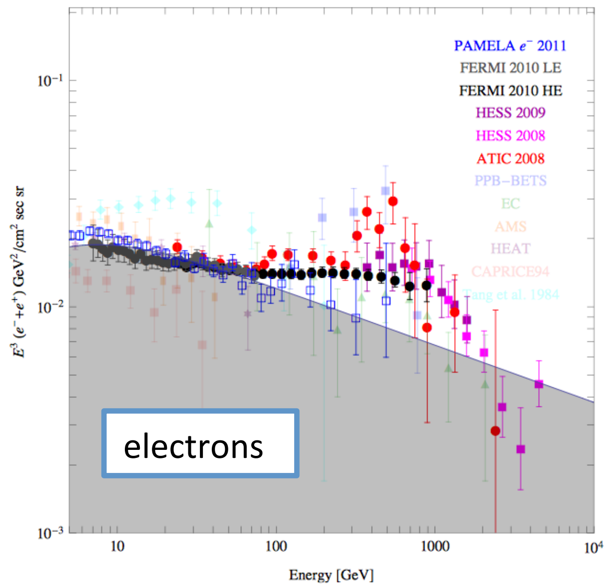


High-Energy processes in astronomical sources
…and indirect search for DM

***Example 3*: Charged particles from WIMPs**







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Cirelli '12

Outline of the three lectures

Lecture 1:

Overview of high-energy sky

- Thermal and non-thermal sources
  - Galactic and extragalactic sources

Lecture 2:

Particle acceleration / interaction / radiation mechanisms

- Shock acceleration and acceleration by large scale electric fields
  - Synchrotron, inverse Compton, Bremsstrahlung emission by electrons / positrons
    - Pion production / decay emission from high-energy protons

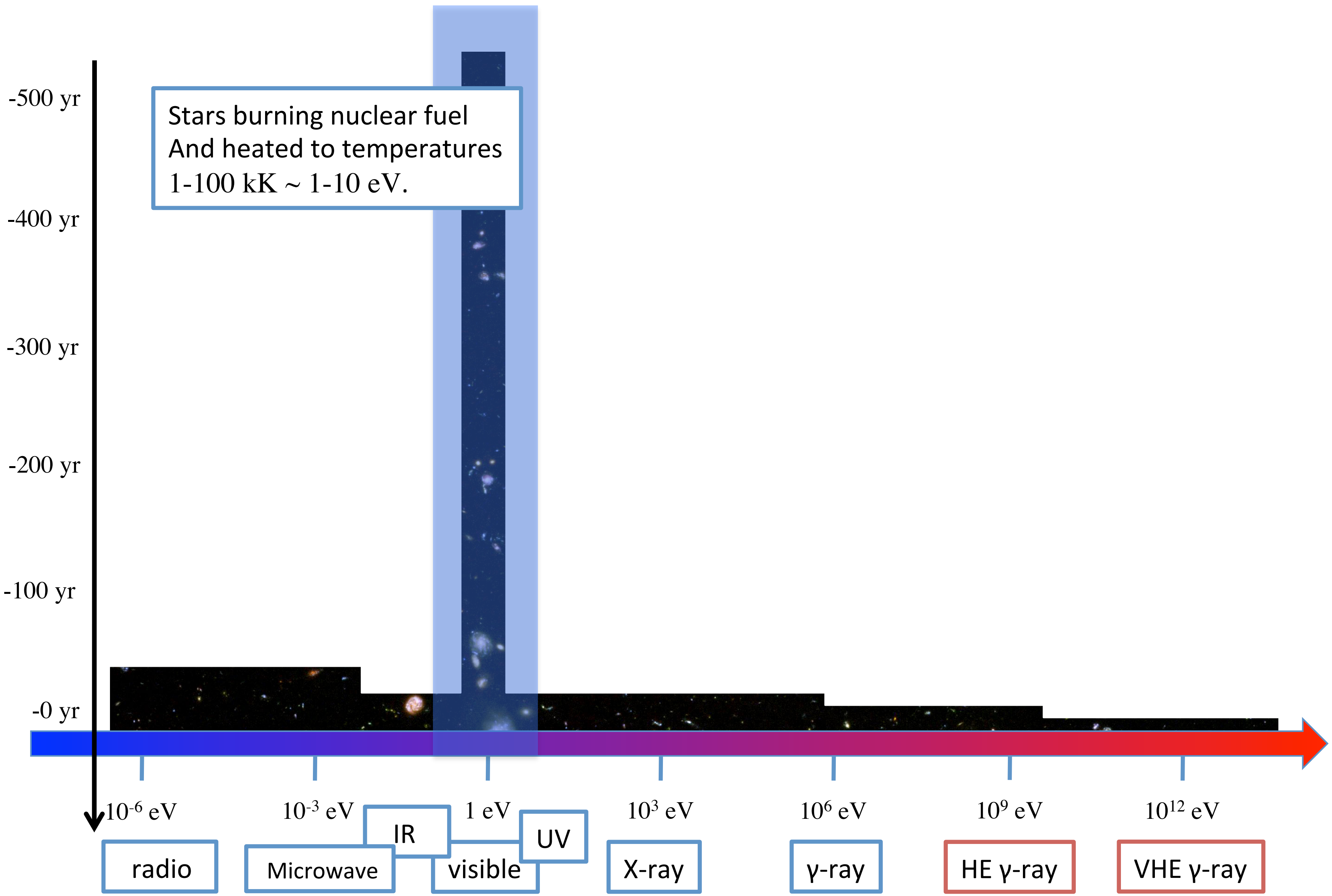
Lecture 3:

Physics of high-energy sources (selected examples)

- Pulsars / pulsar wind nebulae
  - Active galactic nuclei and blazars
    - The Galactic Center

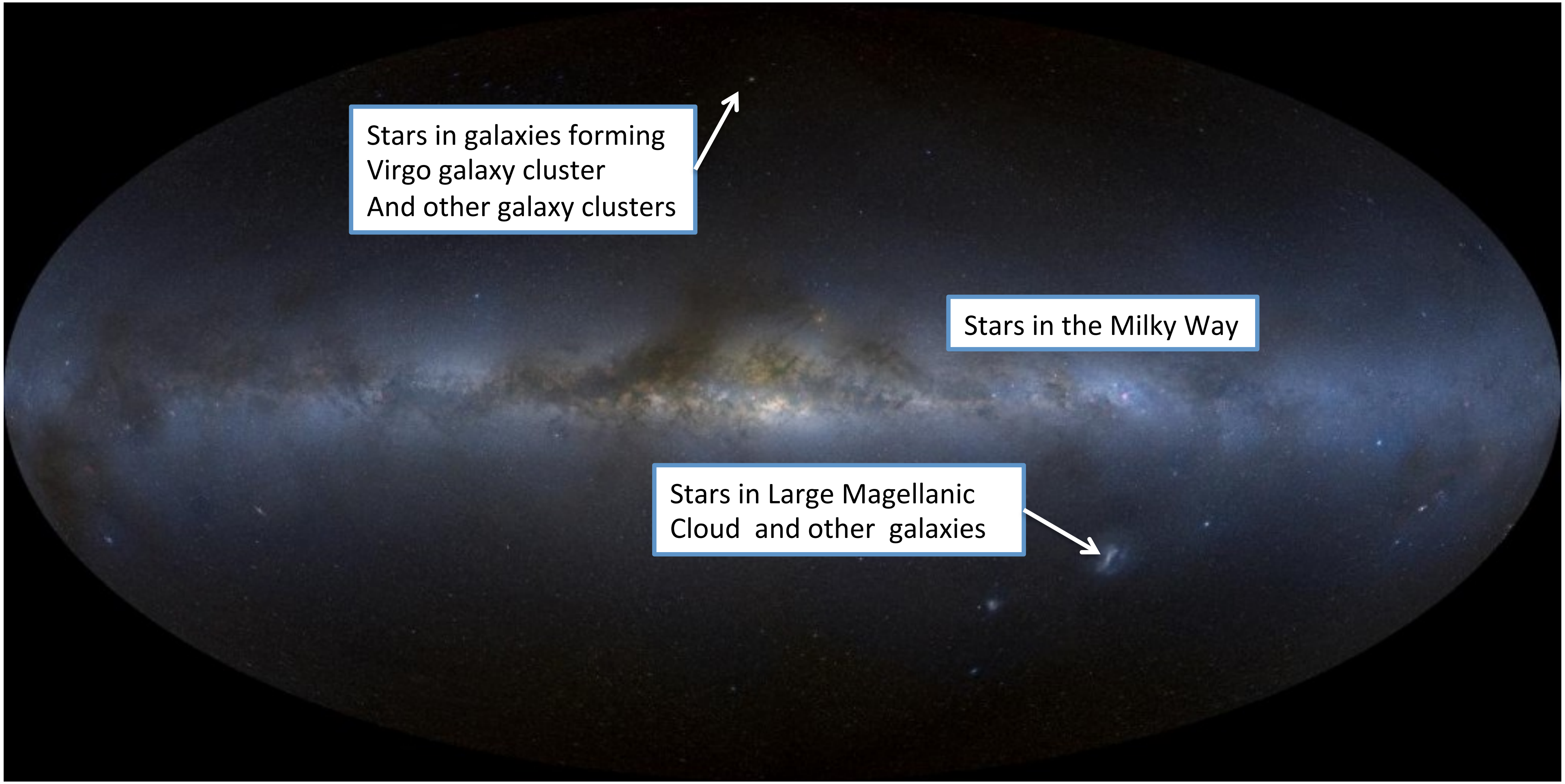
Overview of high-energy sky

"Thermal" Universe

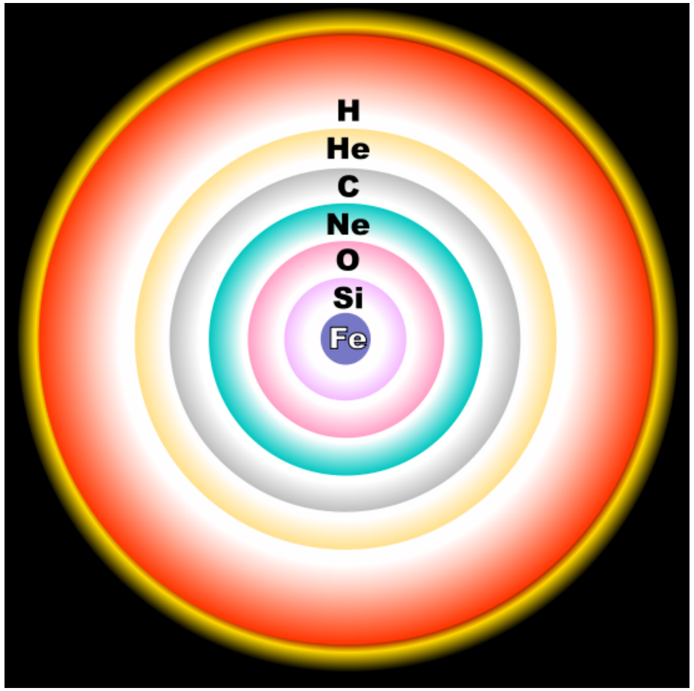


“Thermal” Universe

Visible band



Massive stars



Massive stars are objects emitting at the "Eddington limit", when gravitational attraction is counteracted by the force of radiation pressure

$$\frac{G_N M m_p}{R^2} \sim \frac{\sigma_T L}{4\pi R^2};$$

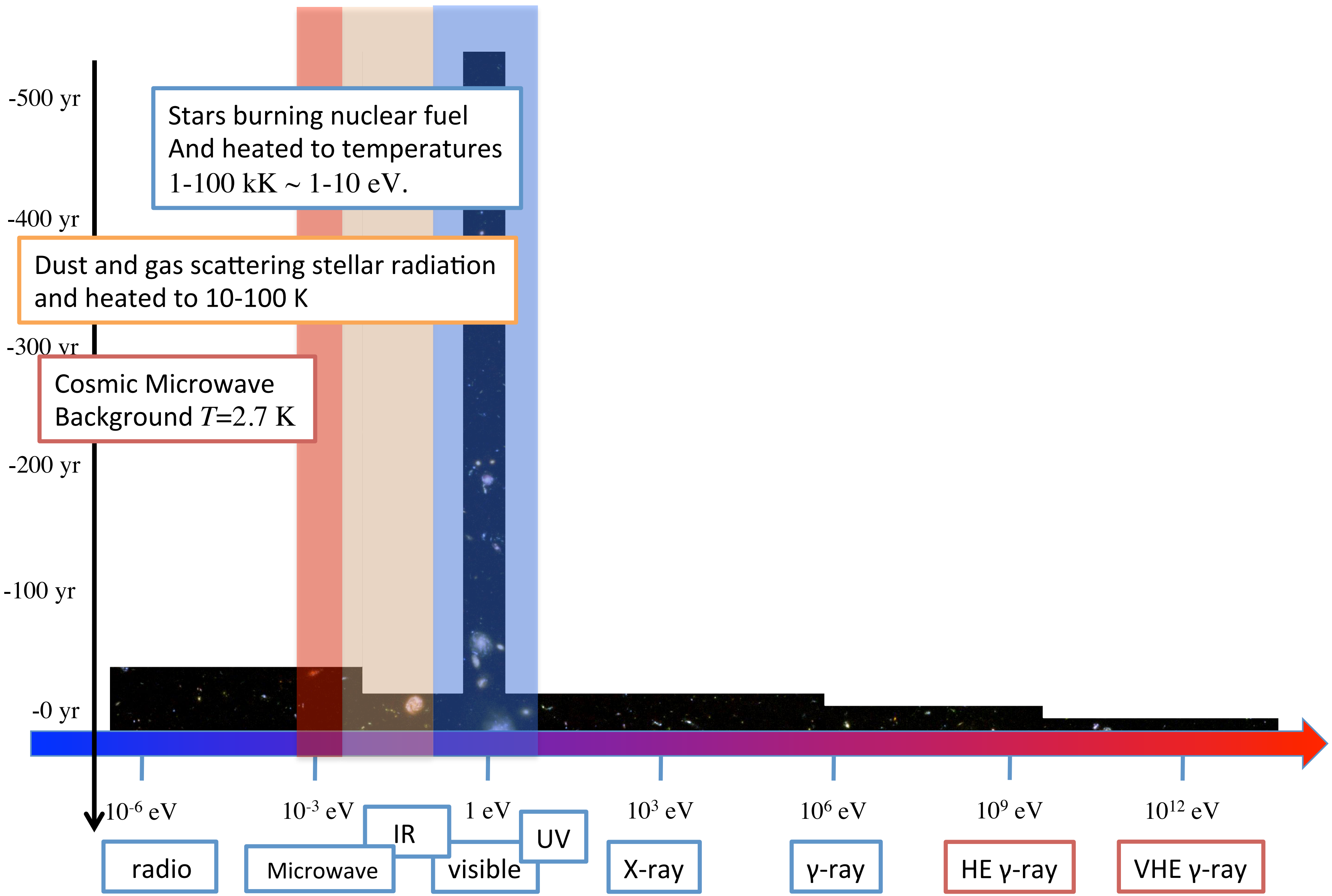
$$L = \frac{4\pi G_N M m_p}{\sigma_T} \simeq 10^{38}\left[\frac{M}{M_\odot}\right] \text{erg/s}$$

(σ_T is the Thomson cross-section) and heated to temperatures 10-100 eV by the releases of gravitational and nuclear energy.

Stellar evolution cycle ends with the occurrence of a "core" composed of iron. Accumulation of mass in the iron core leads to the phenomenon of gravitational collapse at the moment when the matter pressure in the core is not enough to resist the gravity force.

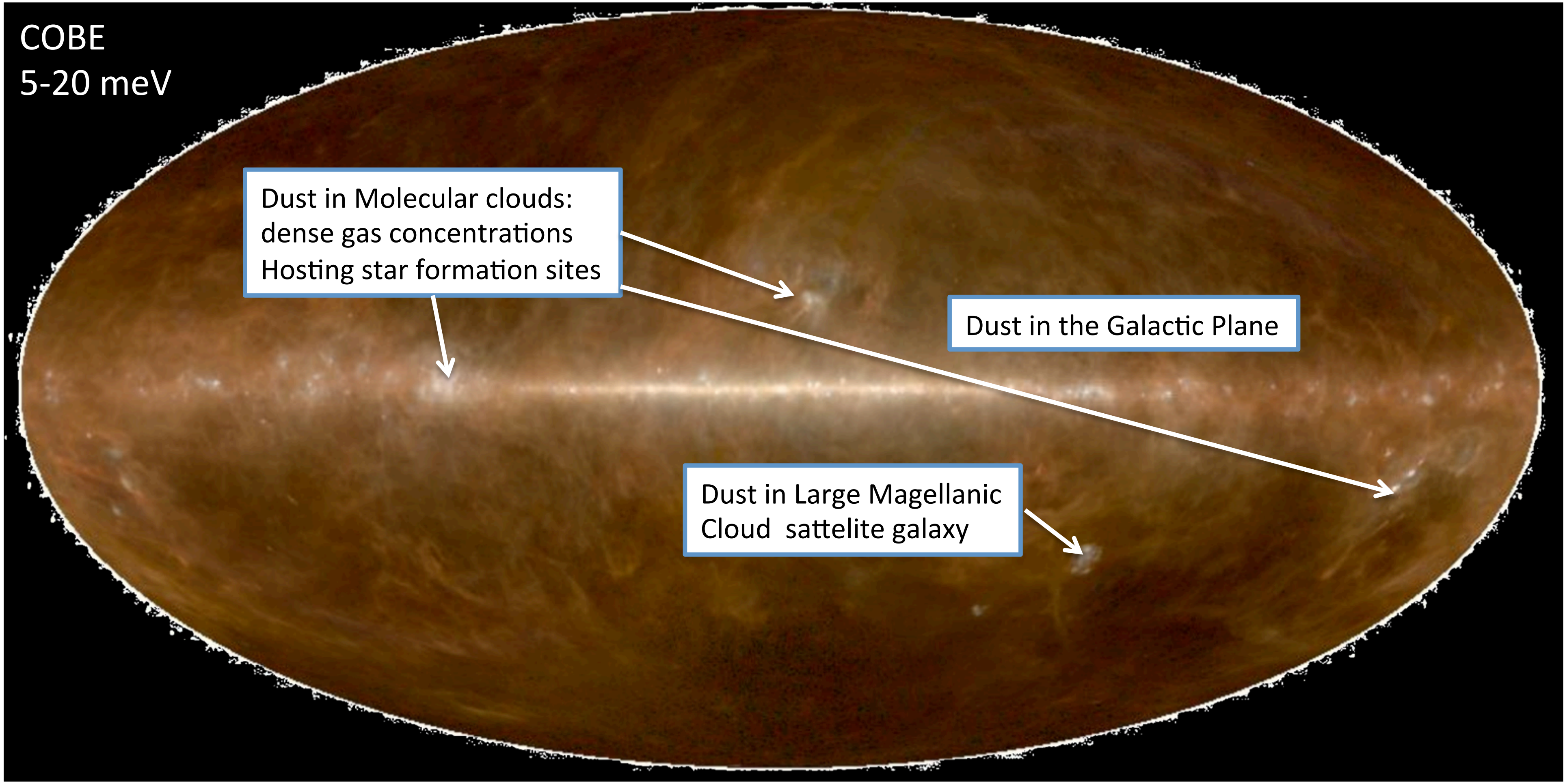
Gravitational collapse could be followed by explosion of **supernova**, which launches an expanding shell of matter into interstellar medium.

“Thermal” Universe



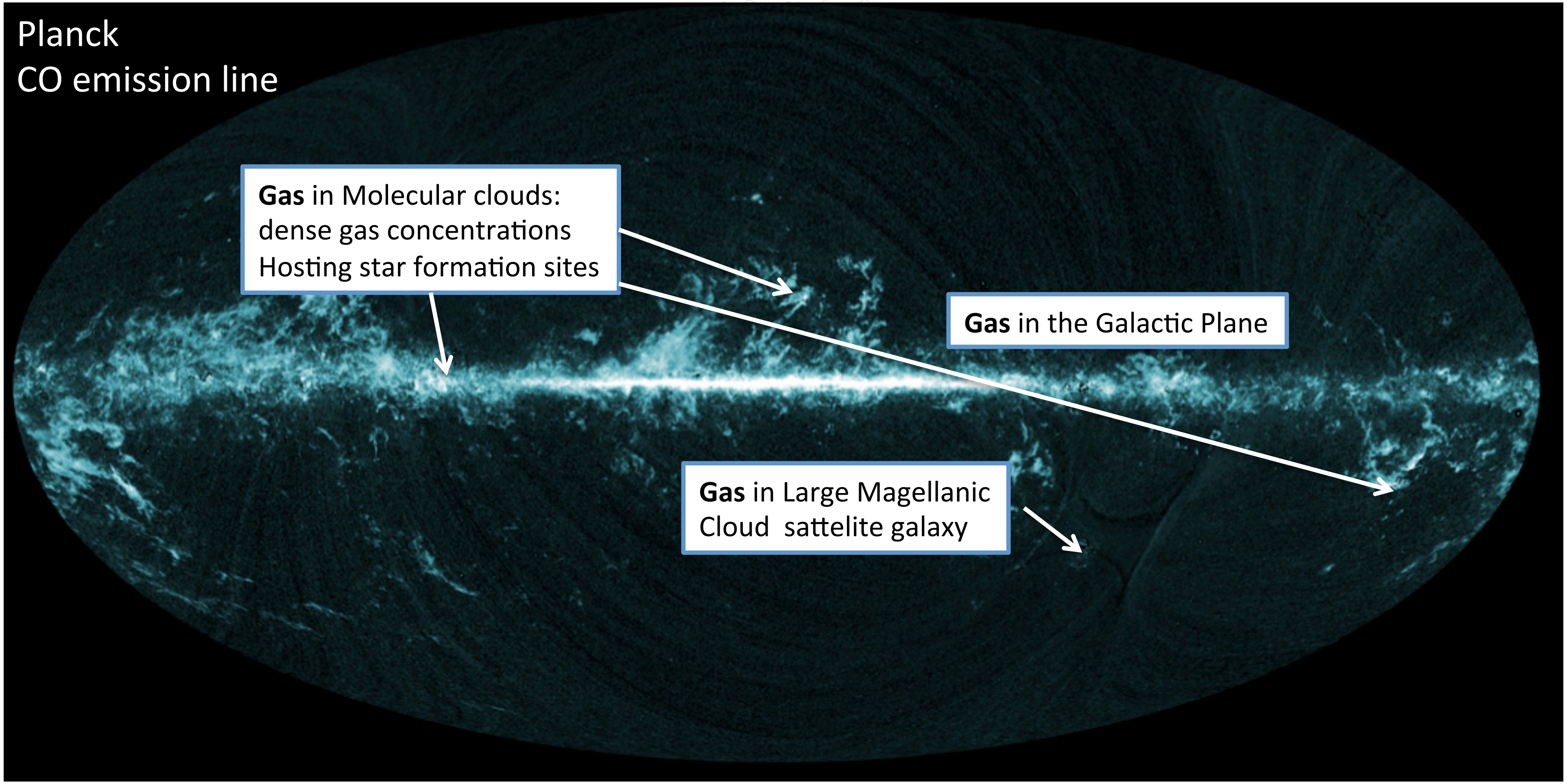
“Thermal” Universe

Far infrared band

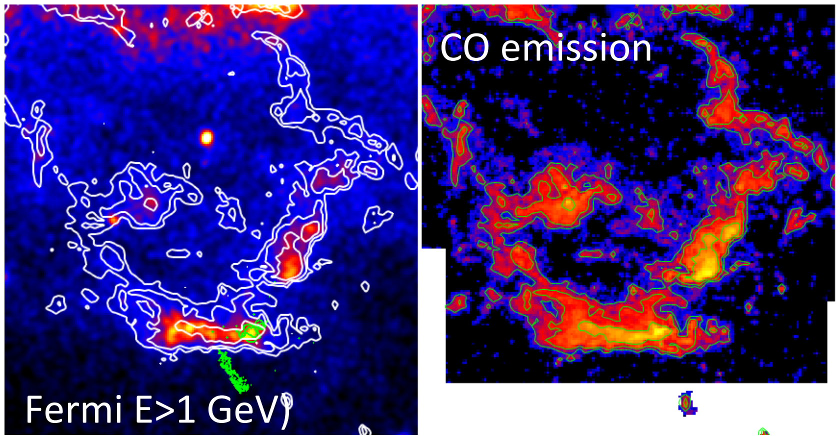


"Thermal" Universe

Far infrared band



Molecular clouds and star formation regions

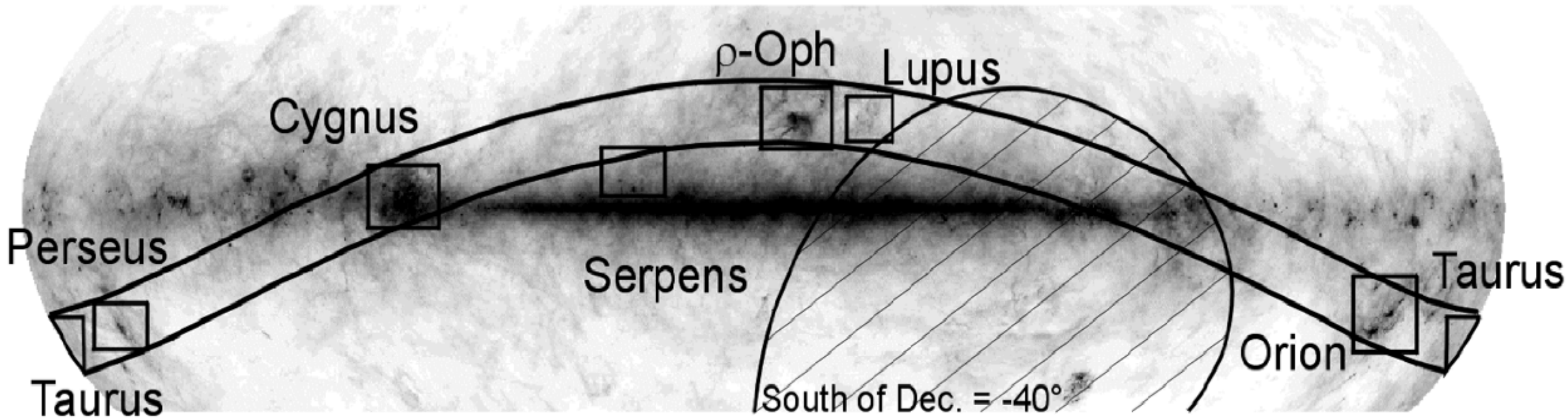


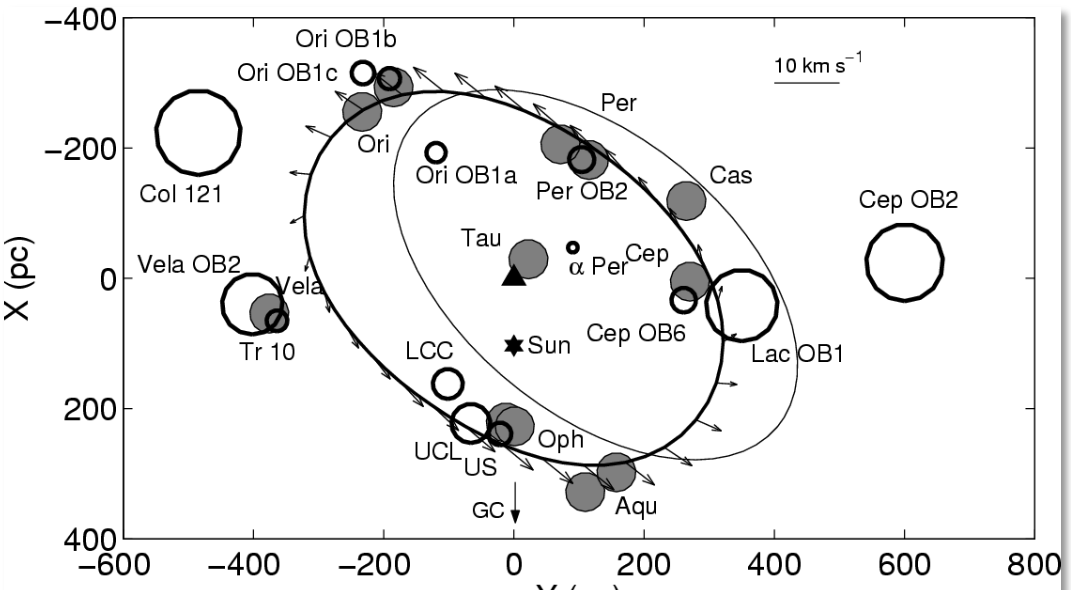
Massive stars mostly form in over-dense and cool regions of the interstellar medium called **Molecular Clouds**. Densities of clouds could reach $10^4 - 10^5$ cm^{-3} (compare with the average density of the Galaxy, 1 cm^{-3}).

High-density gas in the clouds is also a good target material for interactions of high-energy particles present in the interstellar medium.

In the context of indirect DM search, enhanced gamma-ray emission from particle interactions in molecular clouds provides an irreducible background for the search of DM signal from "DM clumps" in the Galaxy.

Molecular clouds and star formation regions

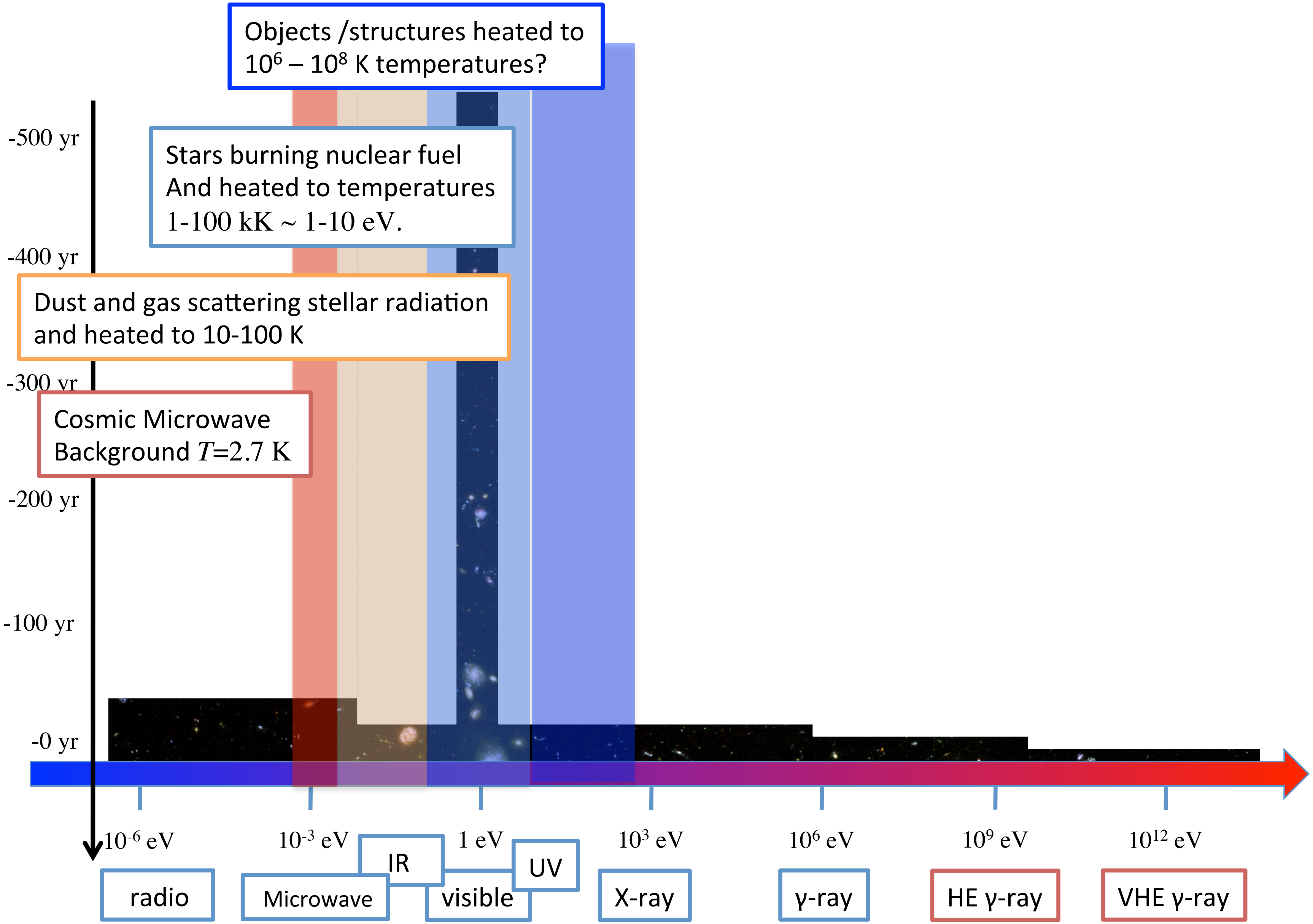




Perrot & Grenier 03

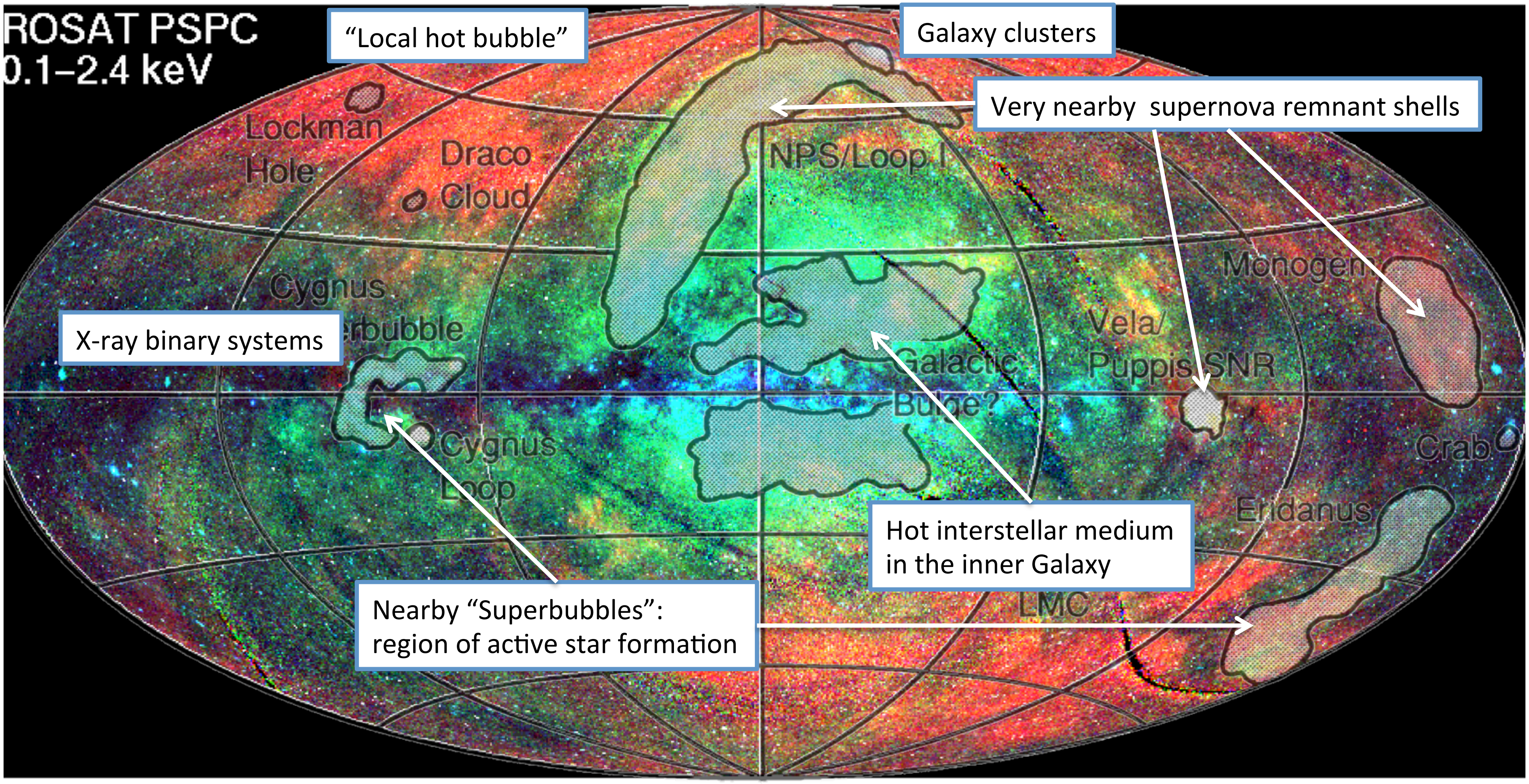
Nearby molecular clouds form an expanding ring called "**Gould Belt**". The diameter of the ring is ~ 1 kpc (3×10^{21} cm), perhaps produced by an explosive event 10^7 yr ago.

“Thermal” Universe



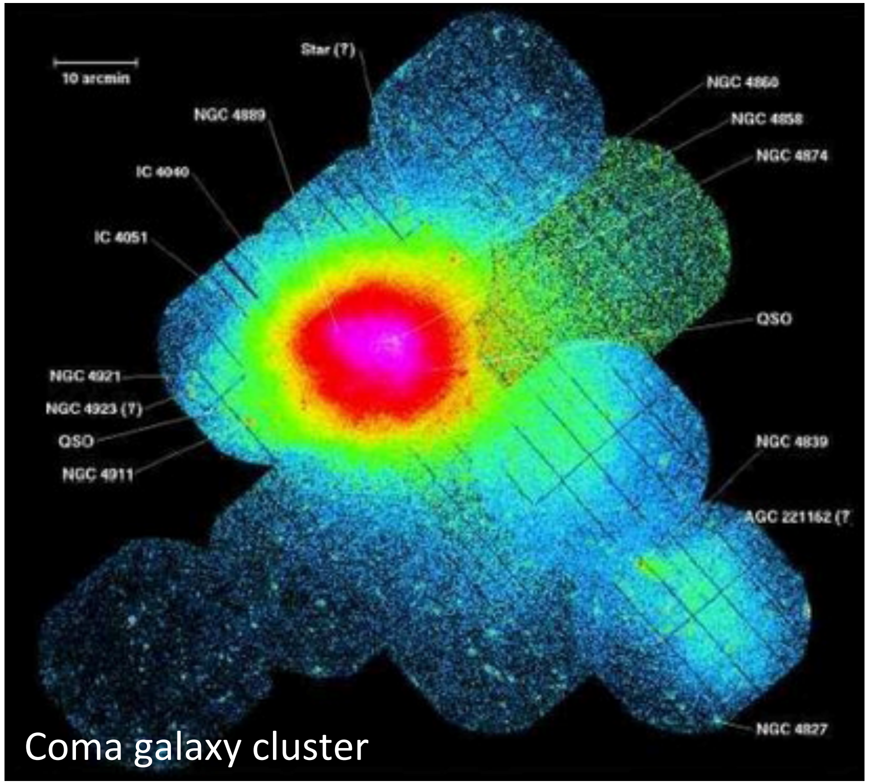
"Thermal" Universe

X-ray band



ROSAT all sky survey map: Red: 0.25 keV
Green: 0.75 keV
Blue: 1.5 keV

Galaxy clusters



Galaxy clusters have temperatures in the $T \sim 10^7$ K range and are strong sources of X-ray emission.

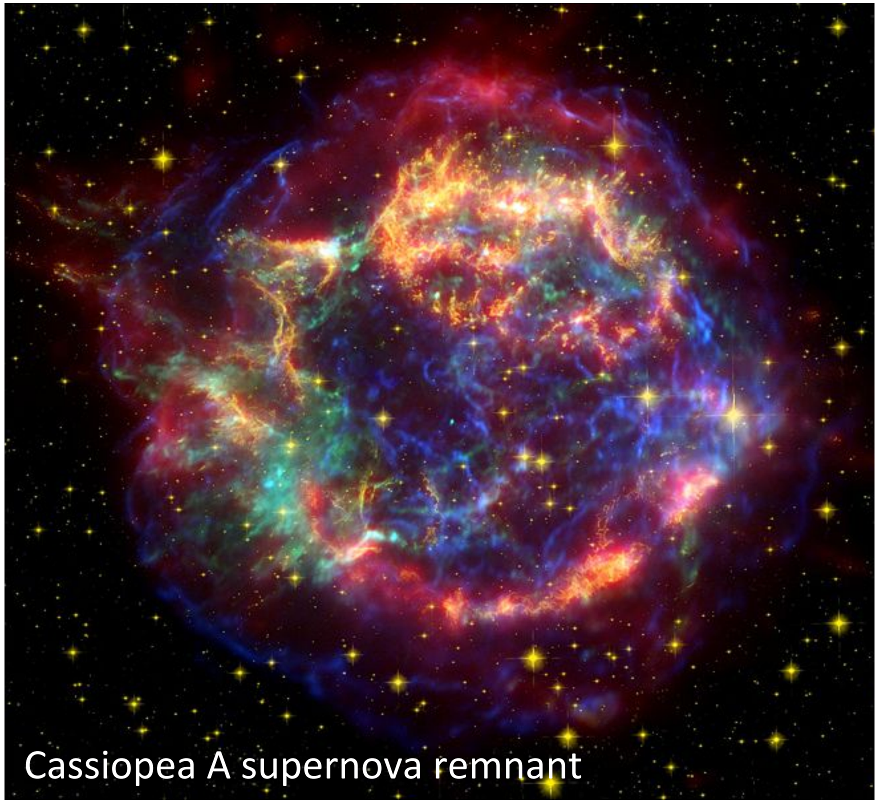
The intracluster medium is heated by the gravitational energy released in the process of cluster formation

$$T \sim \frac{G_N M_{cluster} m}{R_{cluster}}$$

$$\sim 5 \frac{m}{m_p} \left[\frac{M_{cluster}}{10^{14} M_\odot}\right] \left[\frac{R_{cluster}}{1 \text{ Mpc}}\right]^{-1} \text{keV}$$

Thermal X-ray emission from the intracluster gas (Bremsstrahlung and atomic lines) provides strong and complicated background for the search of sterile neutrino DM decay signal.

Supernova remnants



Cassiopea A supernova remnant

Supernova remnants are shells of matter expanding with high velocities into interstellar medium. Kinetic energy of the shell $E_{kin} \sim 10^{51}$ erg, originating from a supernova explosion, is partially converted into heat, giving the temperature

$$T \sim 0.01 - 0.1 \frac{E_{kin}}{M_{\odot} / m_p} \sim 10 - 100 \text{ keV}$$

Hot interstellar medium

Multiple supernova remnants heat the **interstellar medium** and induce interstellar turbulence. Depending on the star formation / supernova explosion rate, thermal energy of particles of interstellar medium might occasionally even exceed the gravitational binding energy

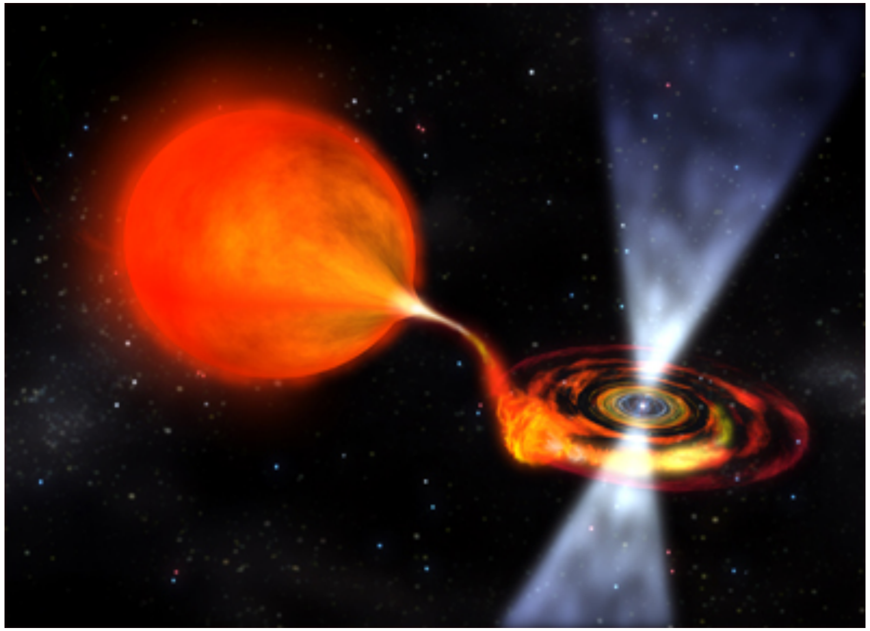
$$T \geq \frac{G_N M_{gal} m}{R_{gal}}$$

$$\sim 0.5 \frac{m}{m_p} \left[\frac{M_{gal}}{10^{12} M_{\odot}} \right] \left[\frac{R_{gal}}{100 \text{ kpc}} \right]^{-1} \text{keV}$$

This leads e.g. to generation of supernova driven **galactic winds** in starburst galaxies.

X-ray emission from the interstellar medium provides complex and irreducible background for the search of DM decay signal from the Galactic halo in X-rays.

X-ray binaries



In **X-ray binaries**, gravitational energy released in the process of accretion of matter onto a compact object (white dwarf, neutron star, black hole) heats the accreting matter up to X-ray temperatures, in the limit when the accretion disk starts to work in the Eddington regime, i.e. when the luminosity reaches the limit

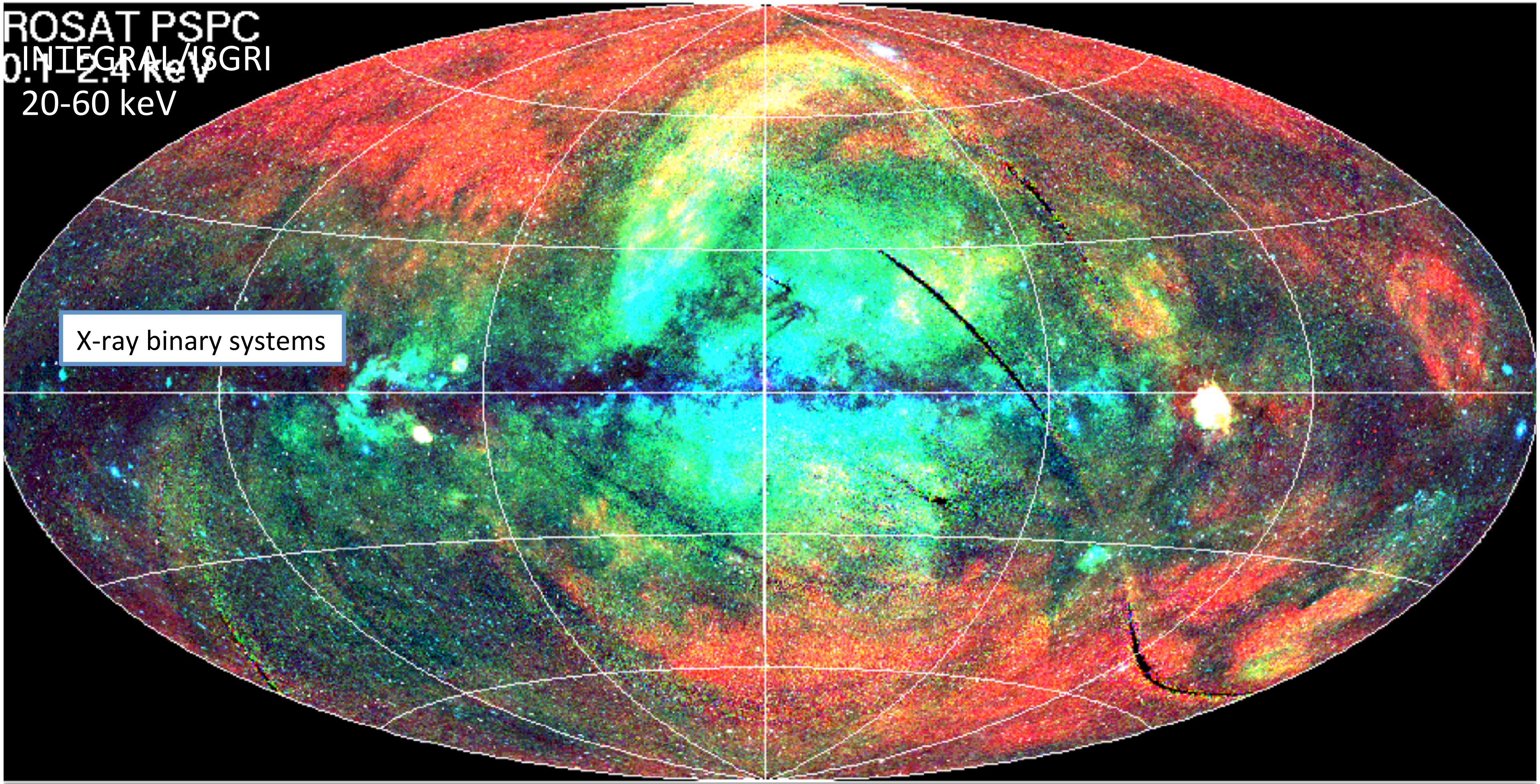
$$L = \frac{4\pi G_N M m_p}{\sigma_T} \simeq 10^{38}\left[\frac{M}{M_\odot}\right] \text{erg/s}$$

Equating this luminosity level to the luminosity of a black body of the size R we find the temperature estimate

$$L = \frac{4\pi G_N M m_p}{\sigma_T} \simeq 4\pi R^2 T^4$$

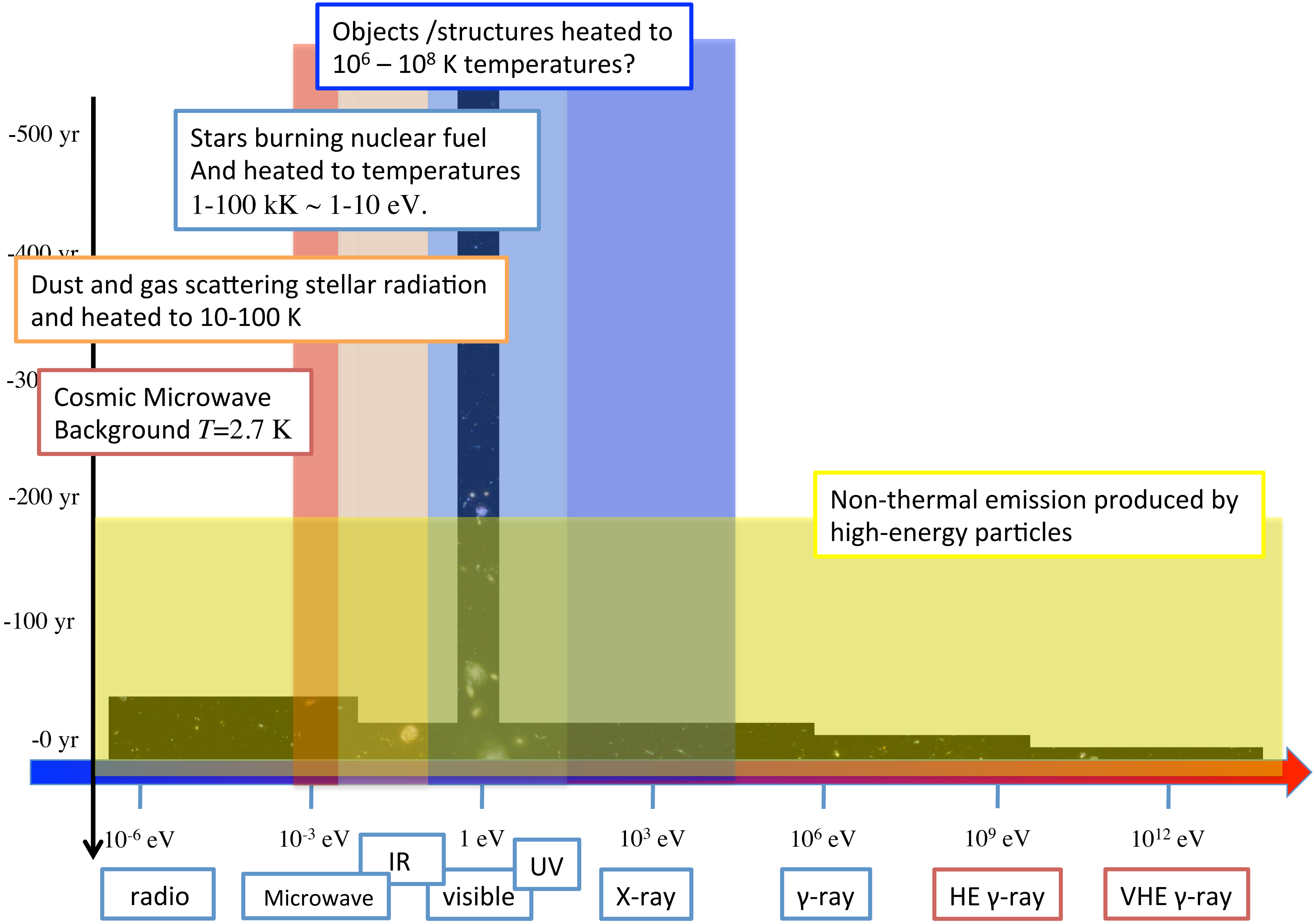
$$T \simeq \left(\frac{G_N M m_p}{\sigma_T R^2}\right)^{1/4} \simeq 1\left[\frac{M}{M_\odot}\right]^{-1/4} \text{keV}$$

X-ray binaries



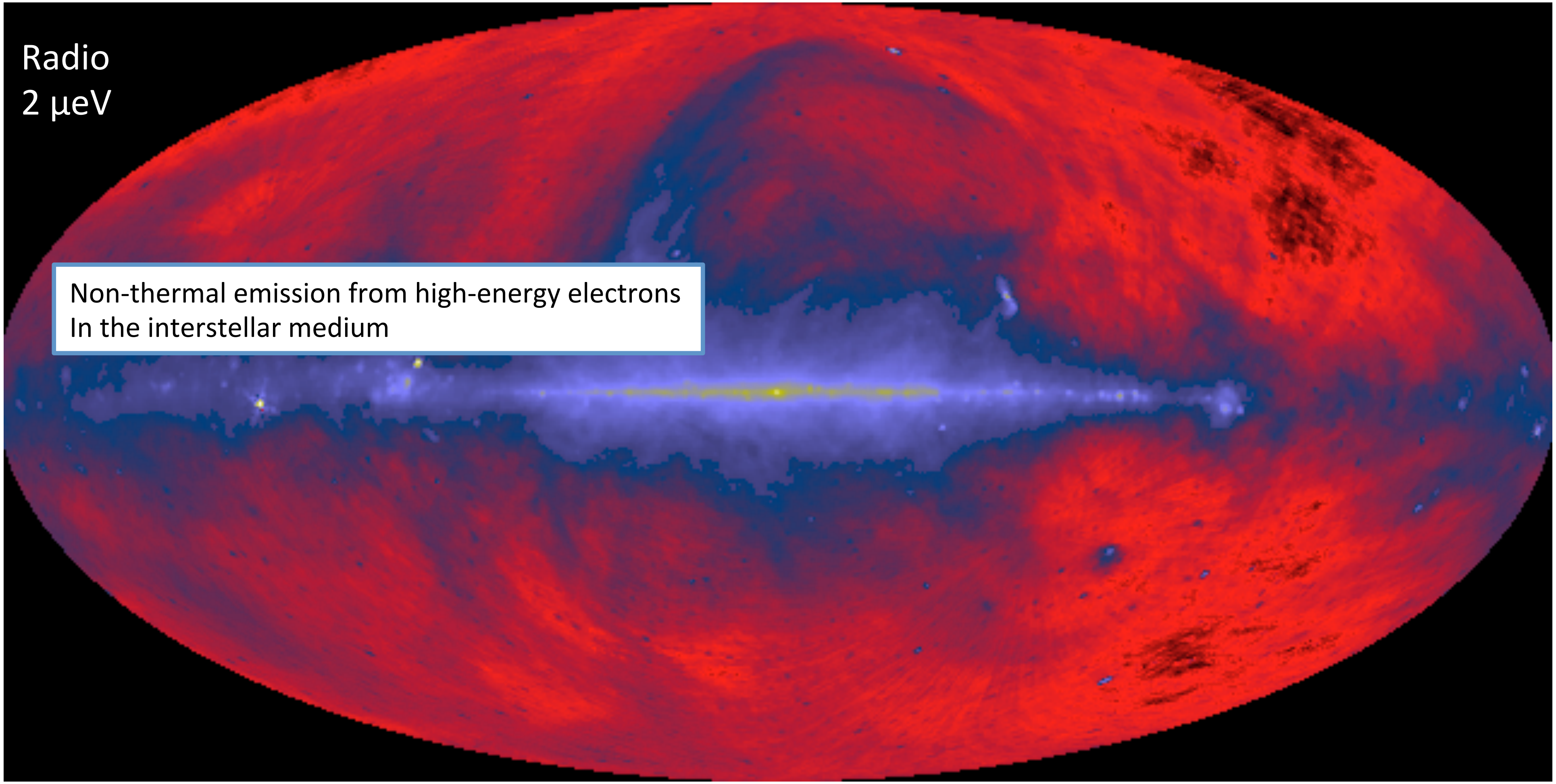
X-ray emitting accretion flows onto stellar mass compact objects dominate in the power budget of the Galaxy in the hard X-ray band.

“Non-thermal” Universe



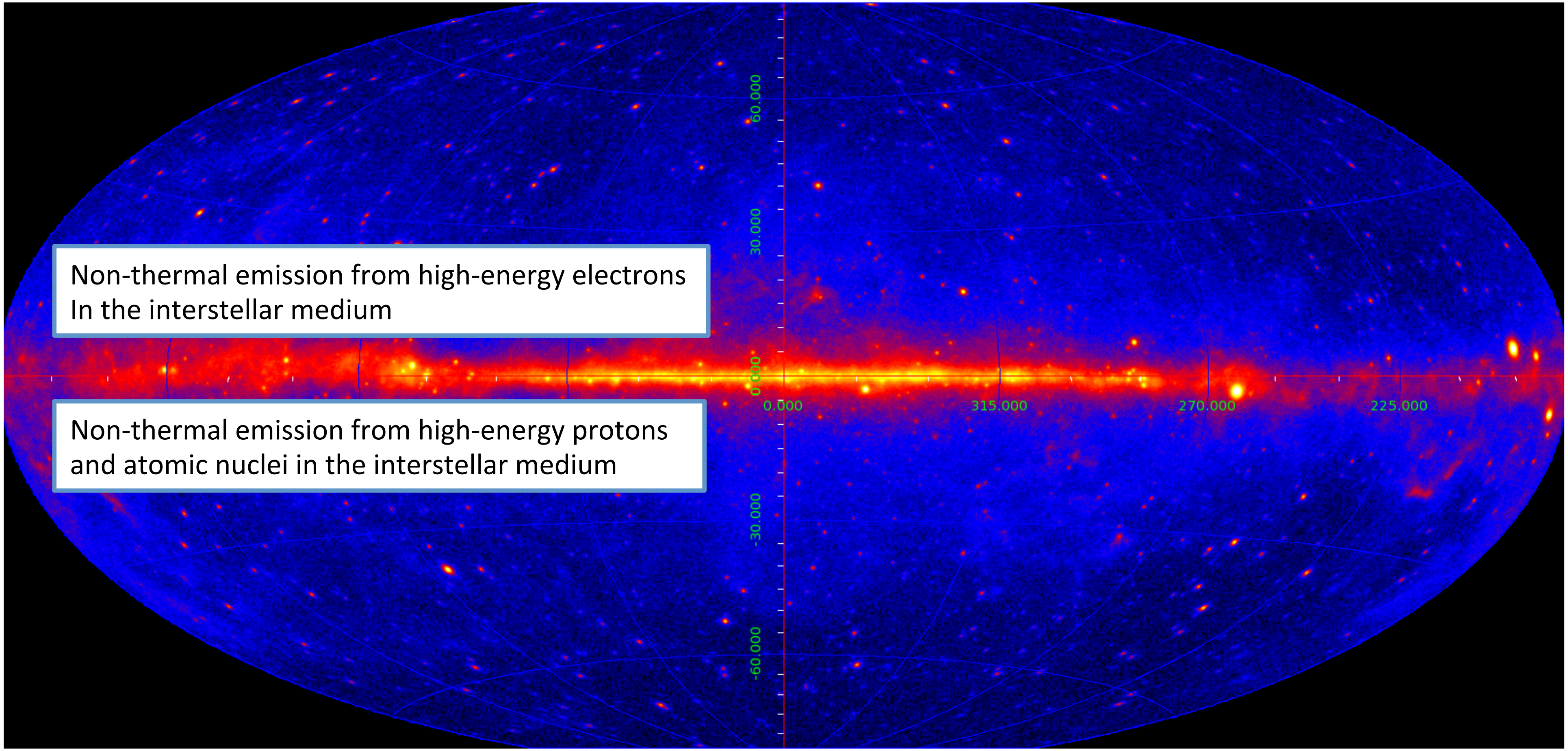
“Non-thermal” Universe

radio band

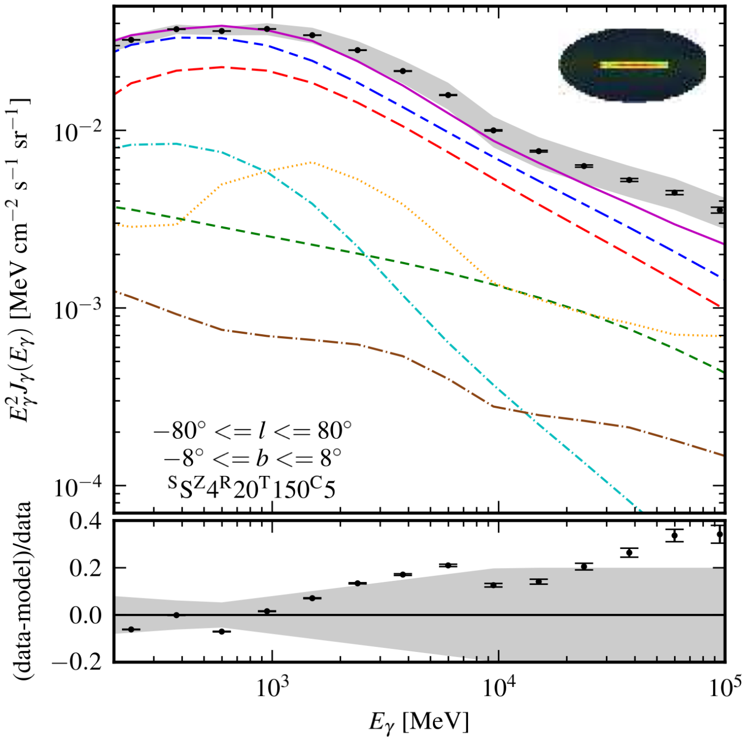


"Non-thermal" Universe

High-energy gamma-ray band



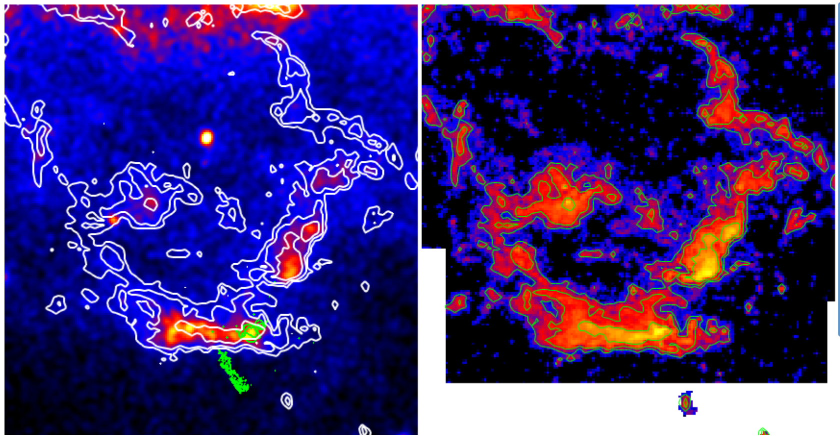
Interstellar medium of the Milky Way



Interactions of high-energy protons, atomic nuclei and electrons in the **interstellar medium** leads to formation of a broad band (radio-to-gamma-ray) Emission spectrum from the entire sky.

Strongest emission is from the inner part of the disk of the Milky Way.

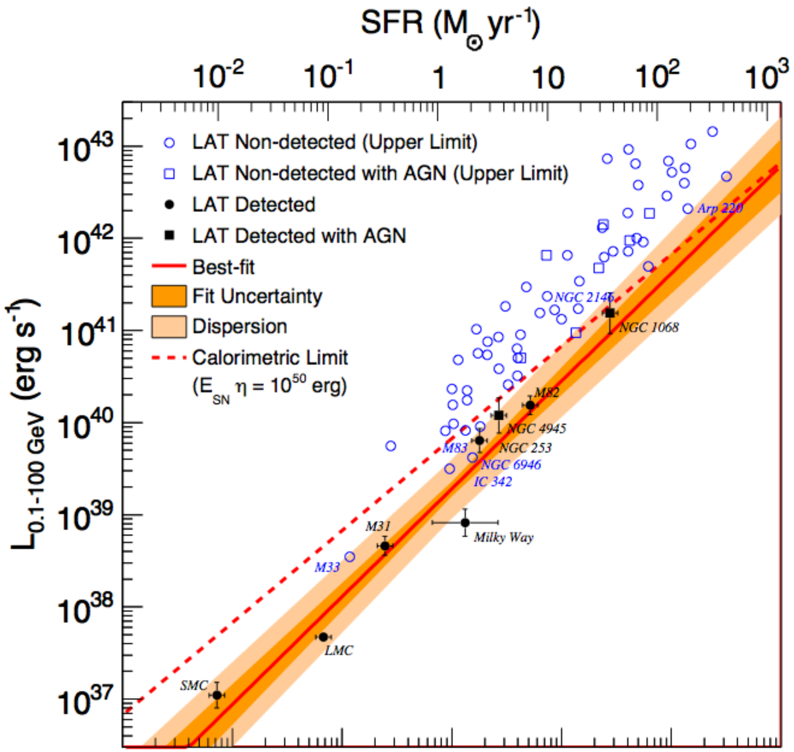
The emission spectrum could be decomposed on contributions from interactions of cosmic ray protons and nuclei (**pion production and decays**) and interactions of cosmic ray electrons (**synchrotron, inverse Compton and Bremsstrahlung** emission).



Volume luminosity of emission from high-energy particle interactions is proportional to the density of the target material in the interstellar medium. This explains correlation of the of gamma-ray emission morphology with the distribution of molecular clouds / star formation regions.

Fermi LAT collab. '12

Interstellar medium of the Milky Way



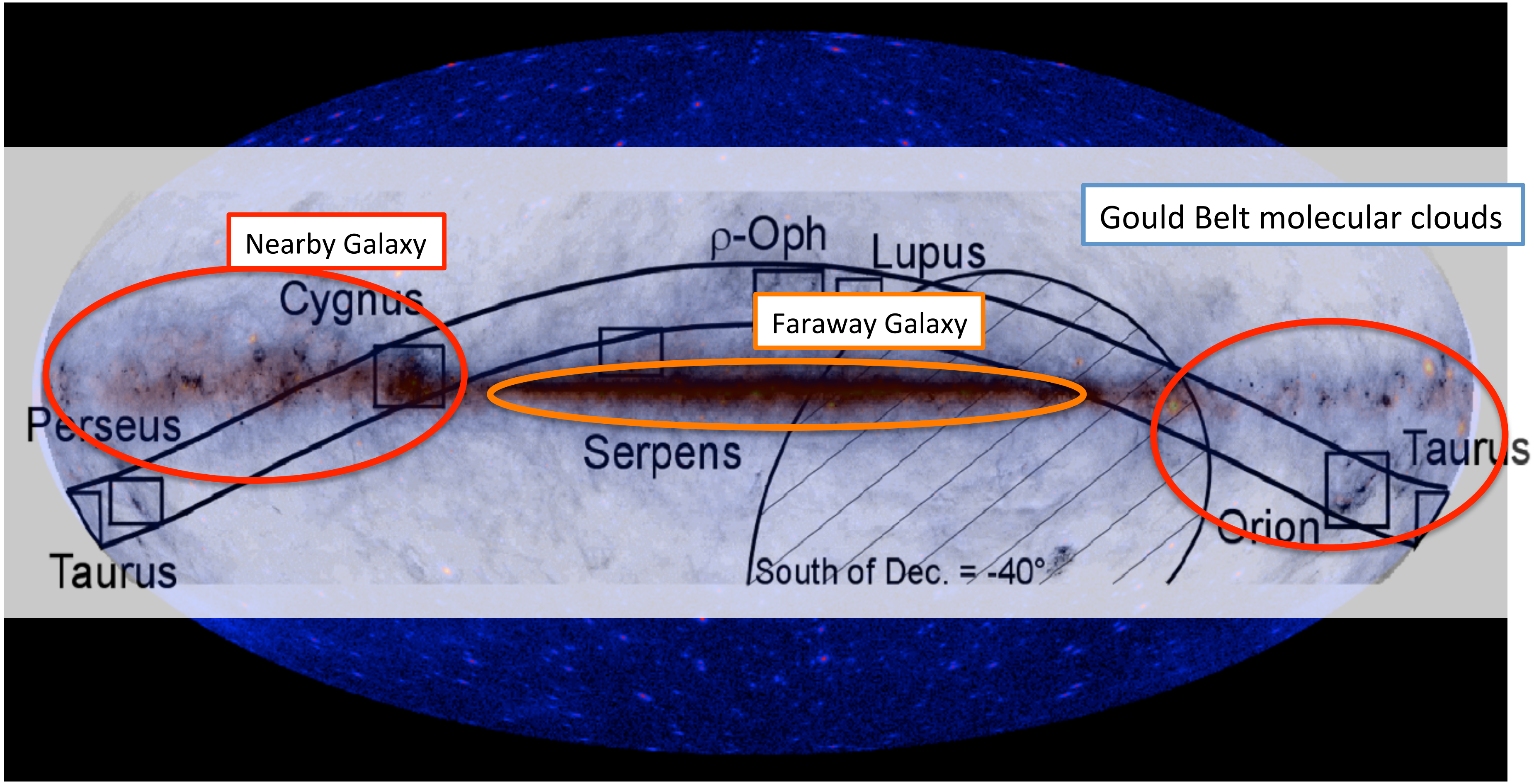
Overall luminosity of non-thermal emission from the interstellar medium is determined by the star formation / supernova explosion rate.

This indicates that injection of high-energy particles in the interstellar medium is a by-product of star formation activity.

This fact provides an additional source of correlation of the intensity of gamma-ray emission with the distribution of molecular clouds / star forming regions.

Fermi LAT Collab. ‘12

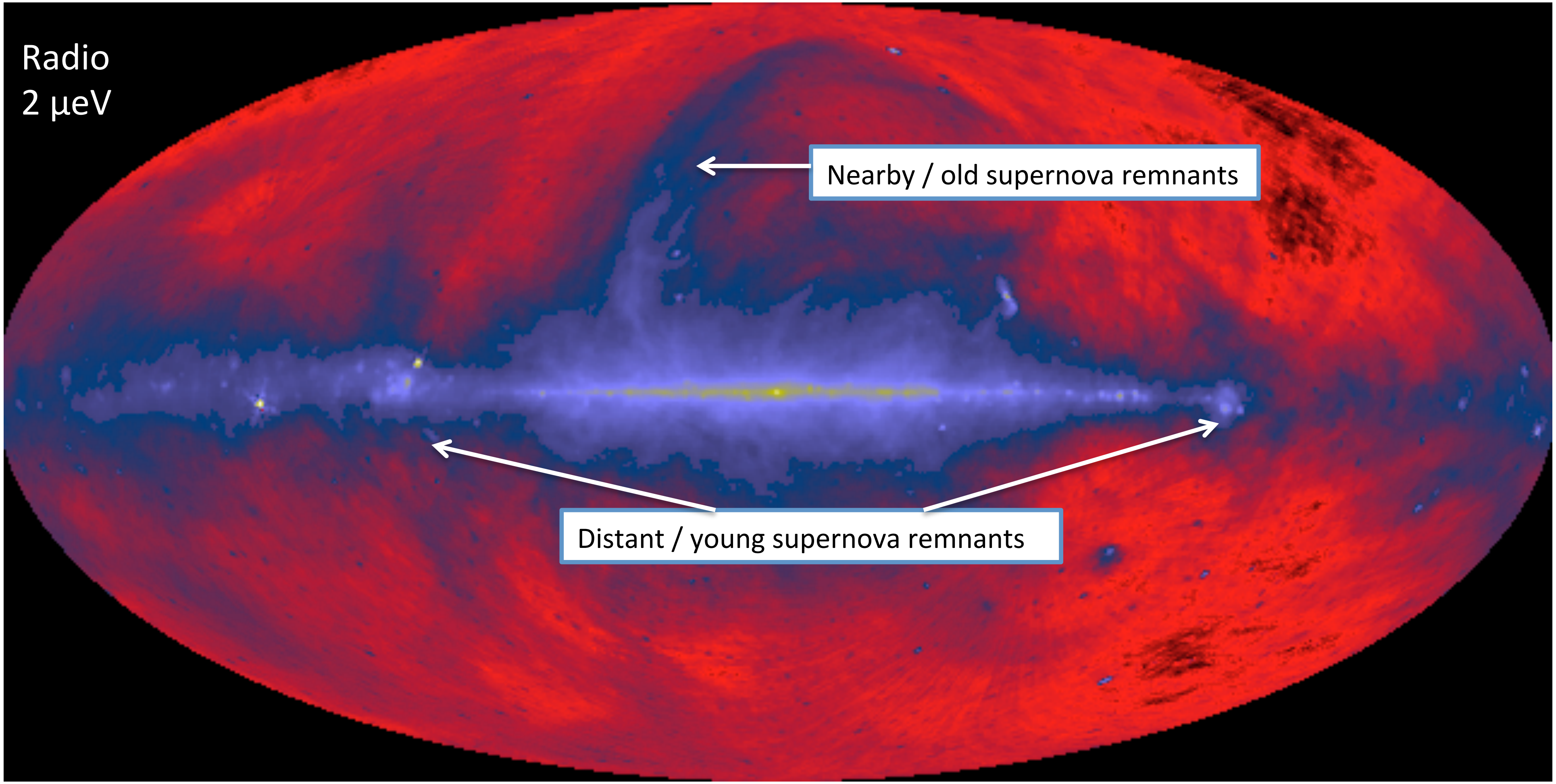
Interstellar medium of the Milky Way



Similarly to the DM, the interstellar medium surrounds us. Its strong radio-to-gamma-ray emission is an irreducible background for the search of DM signal from any direction on the sky.

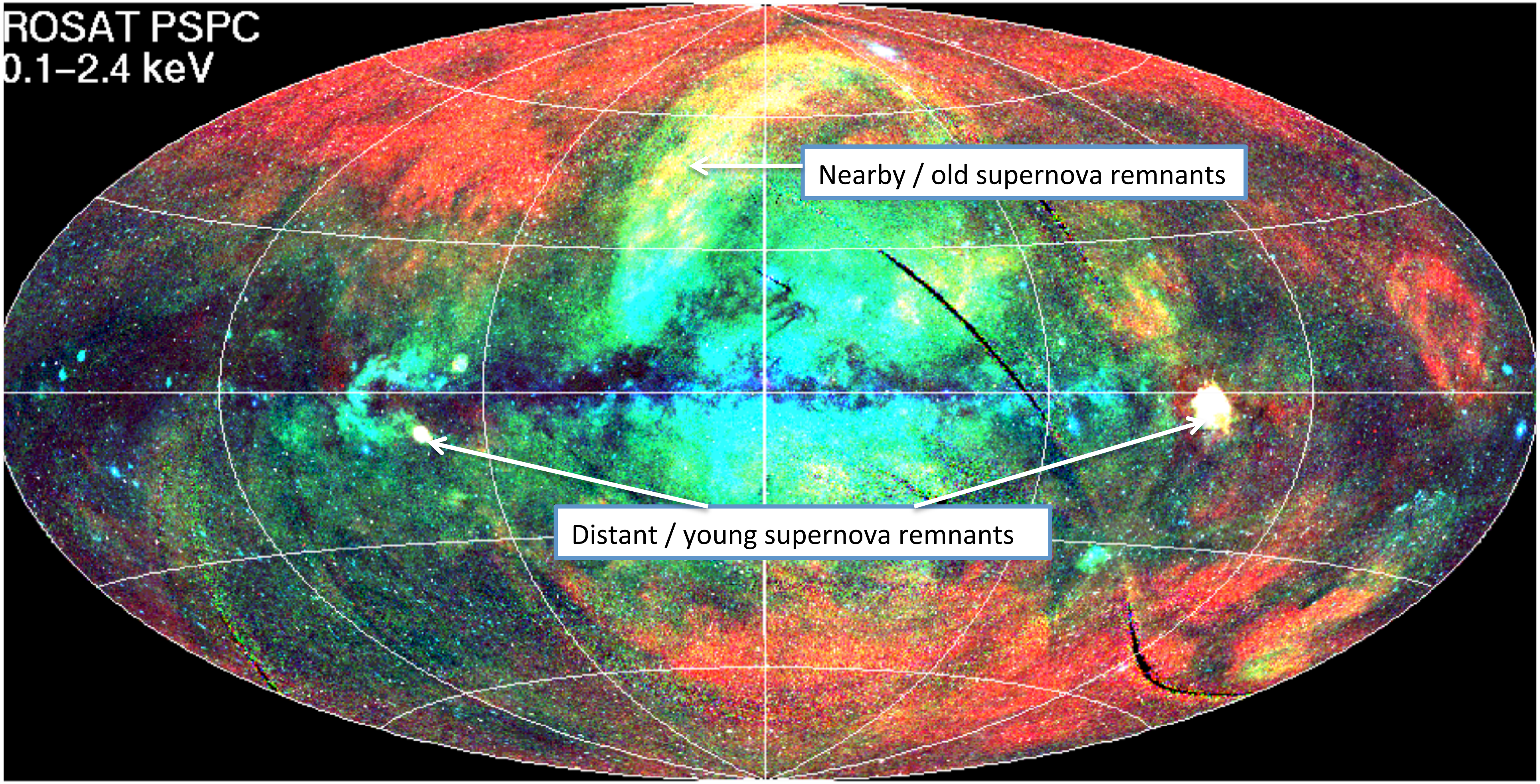
“Non-thermal” Universe

radio band



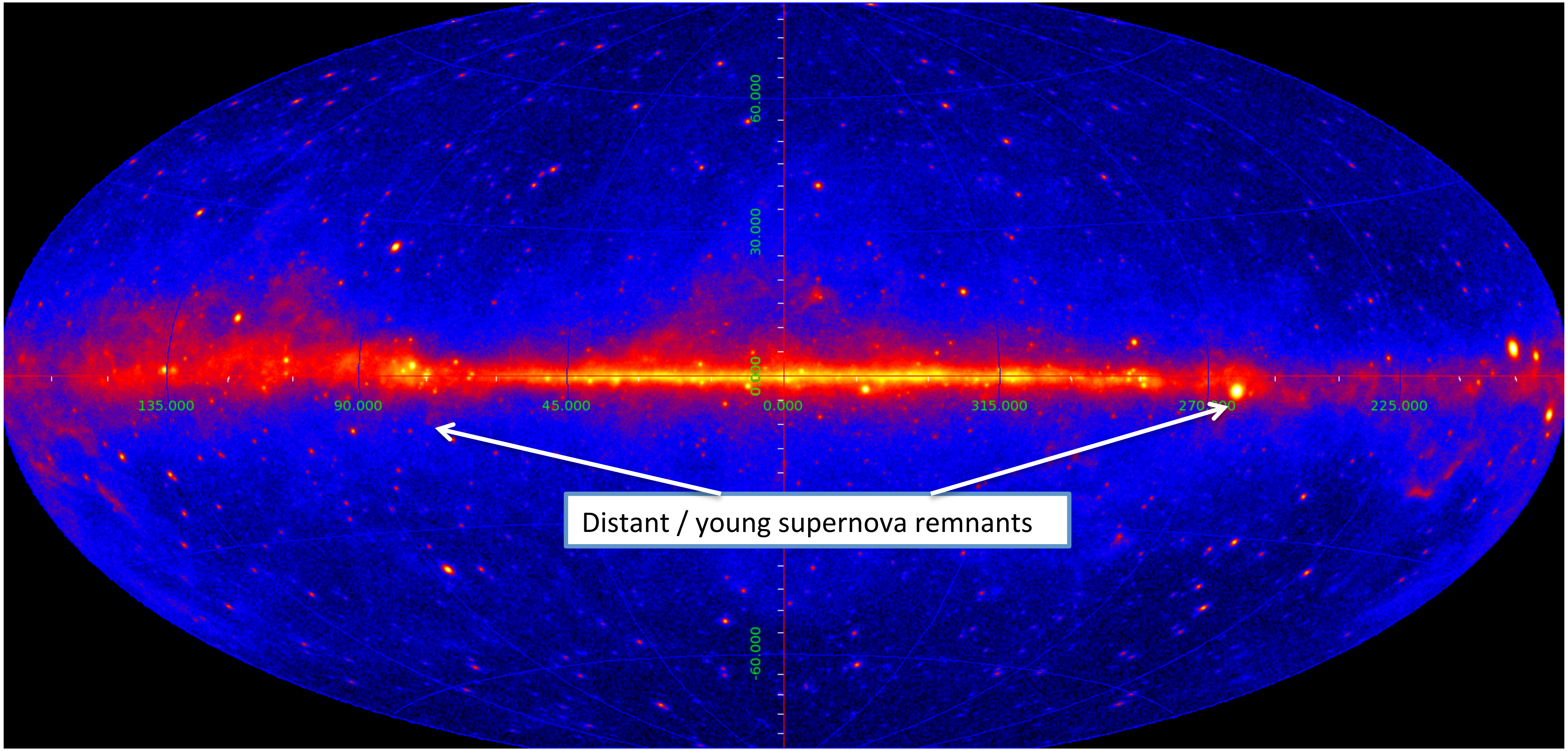
"Non-thermal" Universe

X-ray band

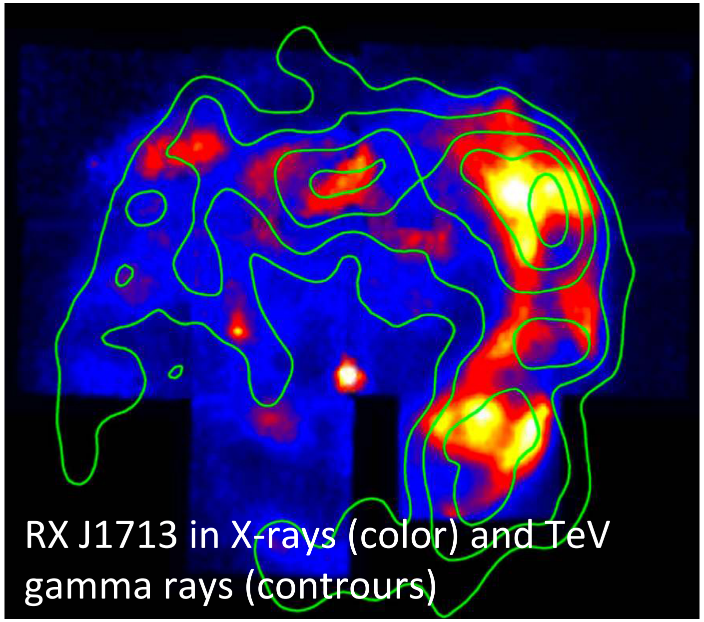


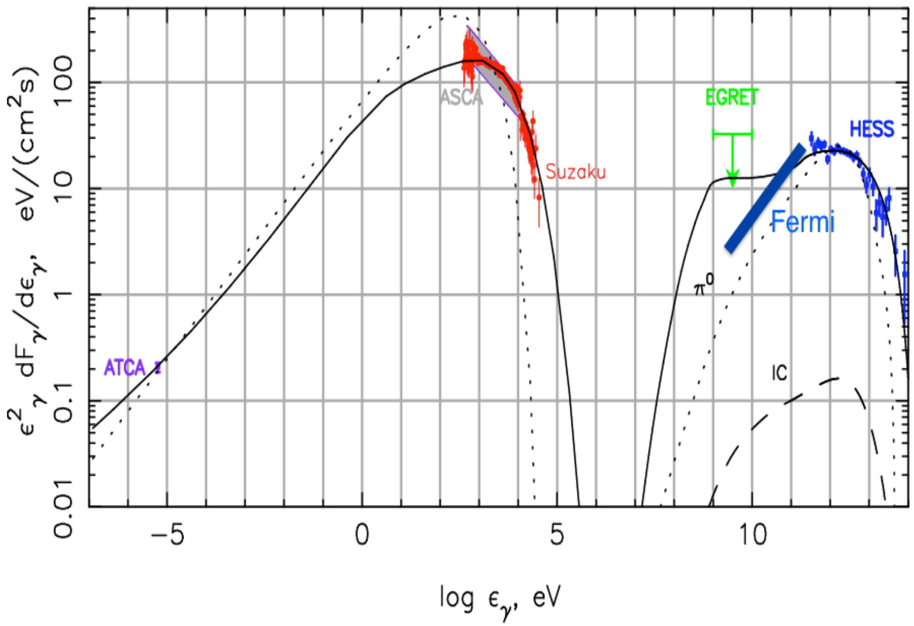
“Non-thermal” Universe

Gamma-ray band



Supernova remnants


RX J1713 in X-rays (color) and TeV gamma rays (contrours)

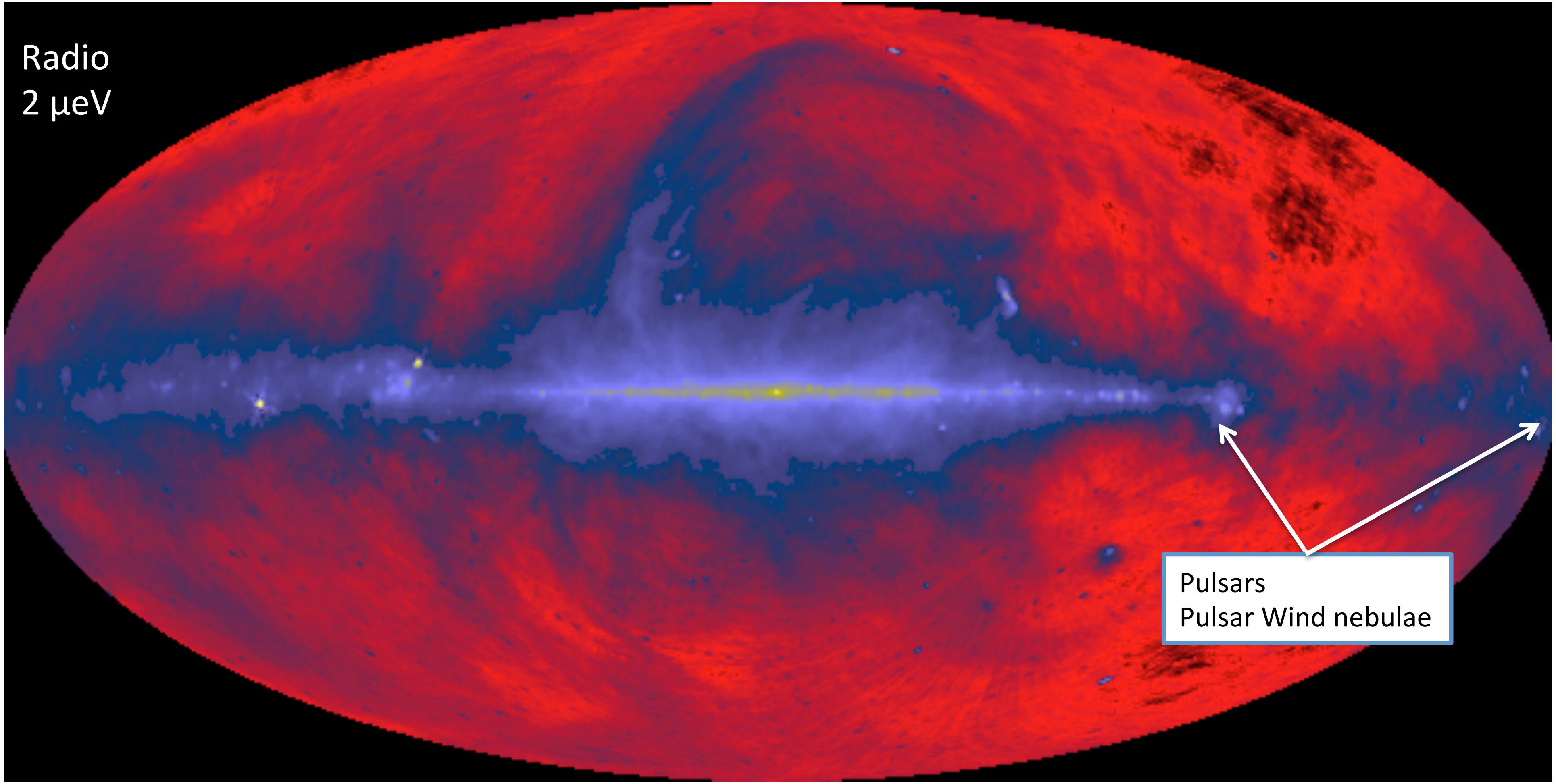


Supernova remnants are not only visible through their thermal X-ray emission, they are also sources of broad band, radio-to-gamma-ray emission produced by high-energy particles captured inside supernova remnant shells.

Non-thermal emission spectra of the remnants could be decomposed onto contributions from the high-energy electrons (**synchrotron, inverse Compton and Bremsstrahlung** emission) and cosmic ray protons and nuclei (**pion production** and decays)

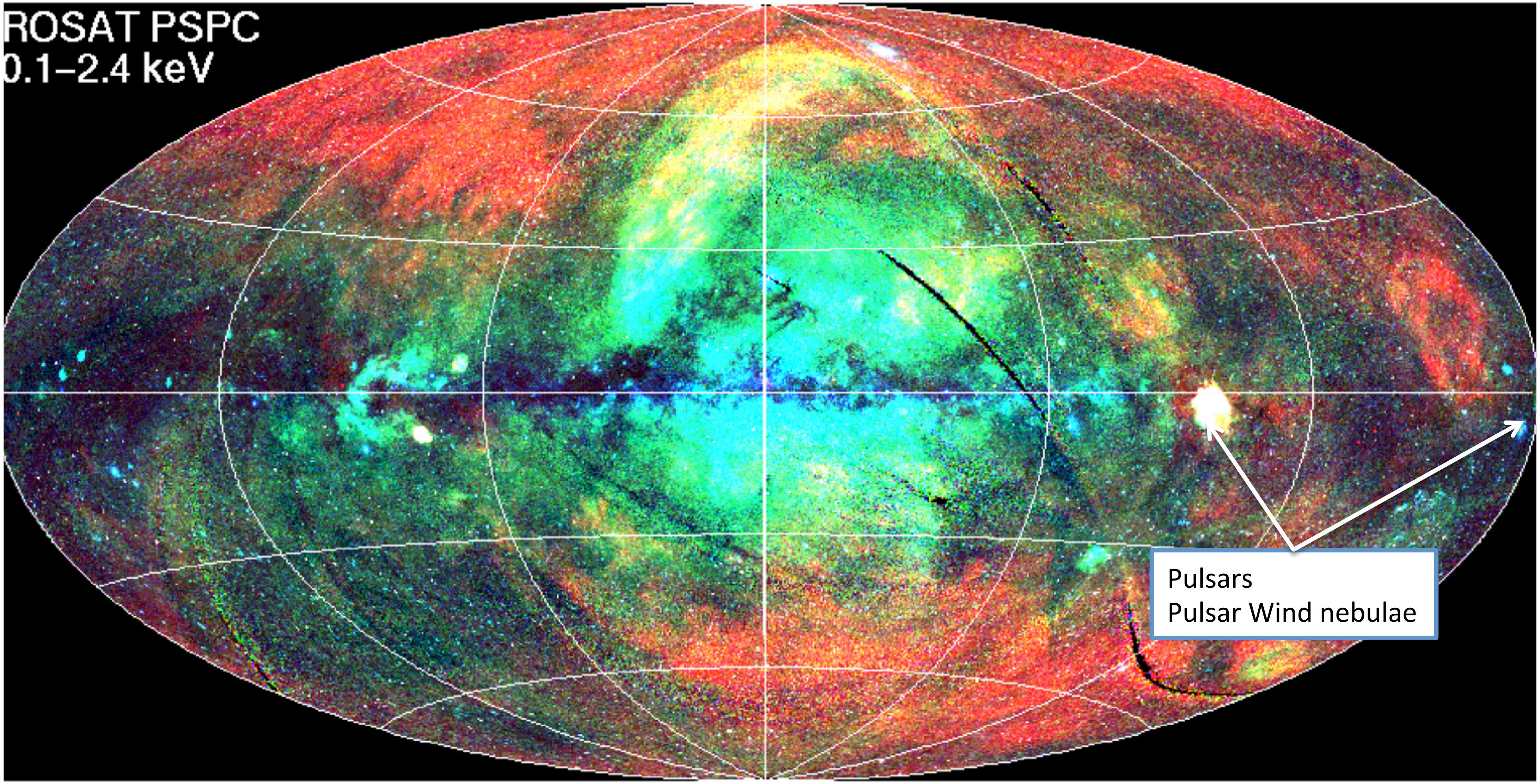
“Non-thermal” Universe

radio band



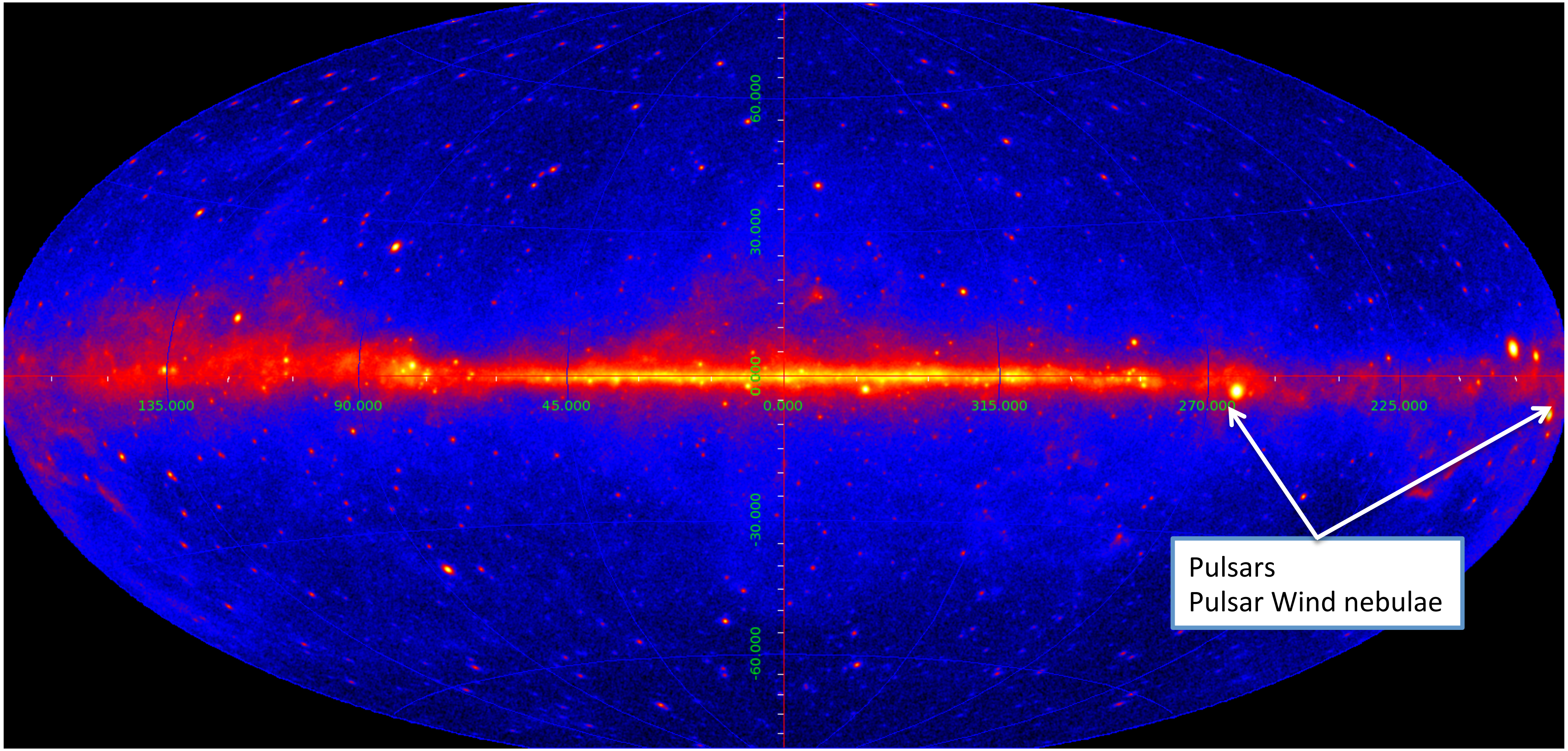
“Non-thermal” Universe

X-ray band

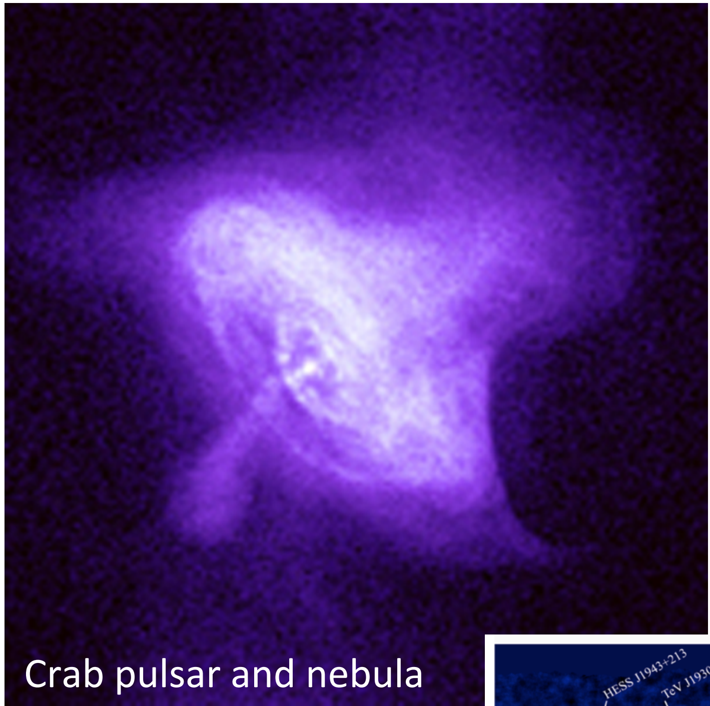


“Non-thermal” Universe

High-energy gamma-ray band



Pulsars and Pulsar Wind Nebulae

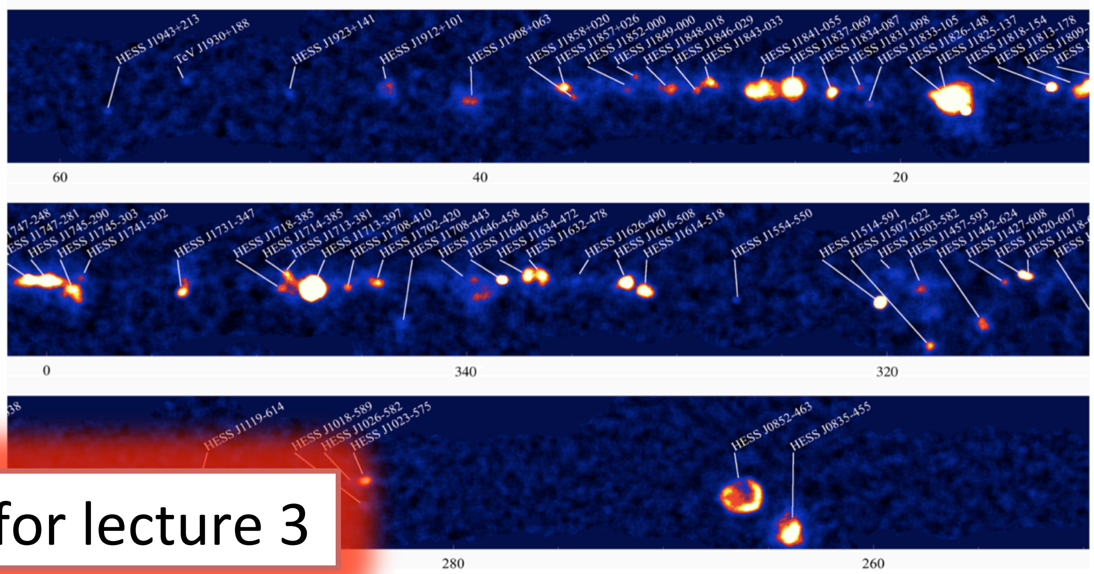


Crab pulsar and nebula

Pulsars are fast rotating neutron stars dissipating their rotation energy via high-energy particle acceleration followed by non-thermal radio-to-gamma-ray emission.

Similarly to supernova remnants, pulsars are produced in supernova explosions and often reside inside the supernova remnants.

Pulsar wind nebulae might be dominant class of Galactic sources in the TeV energy band.

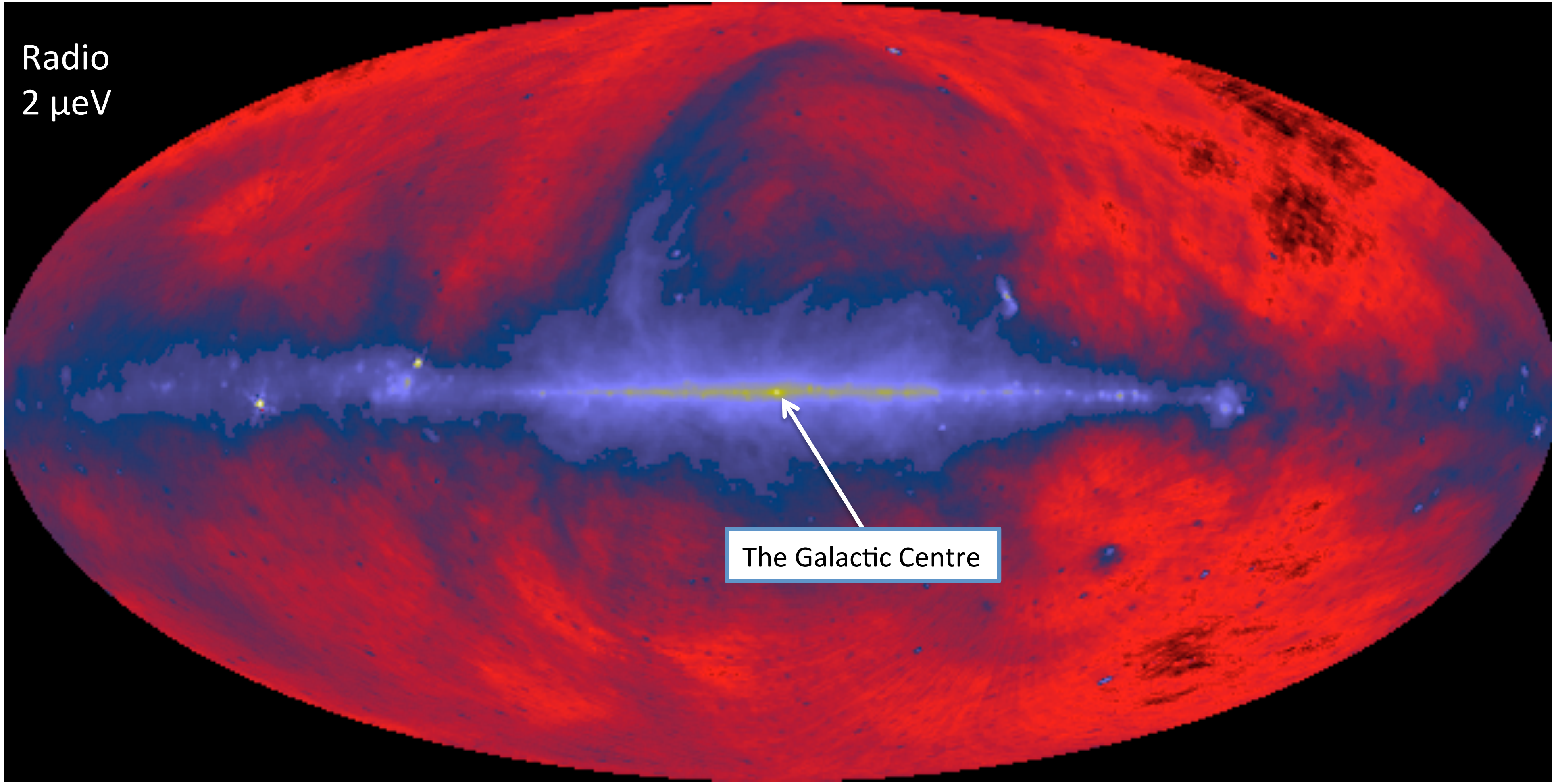


HESS Collab. '14

"Selected" subject for lecture 3

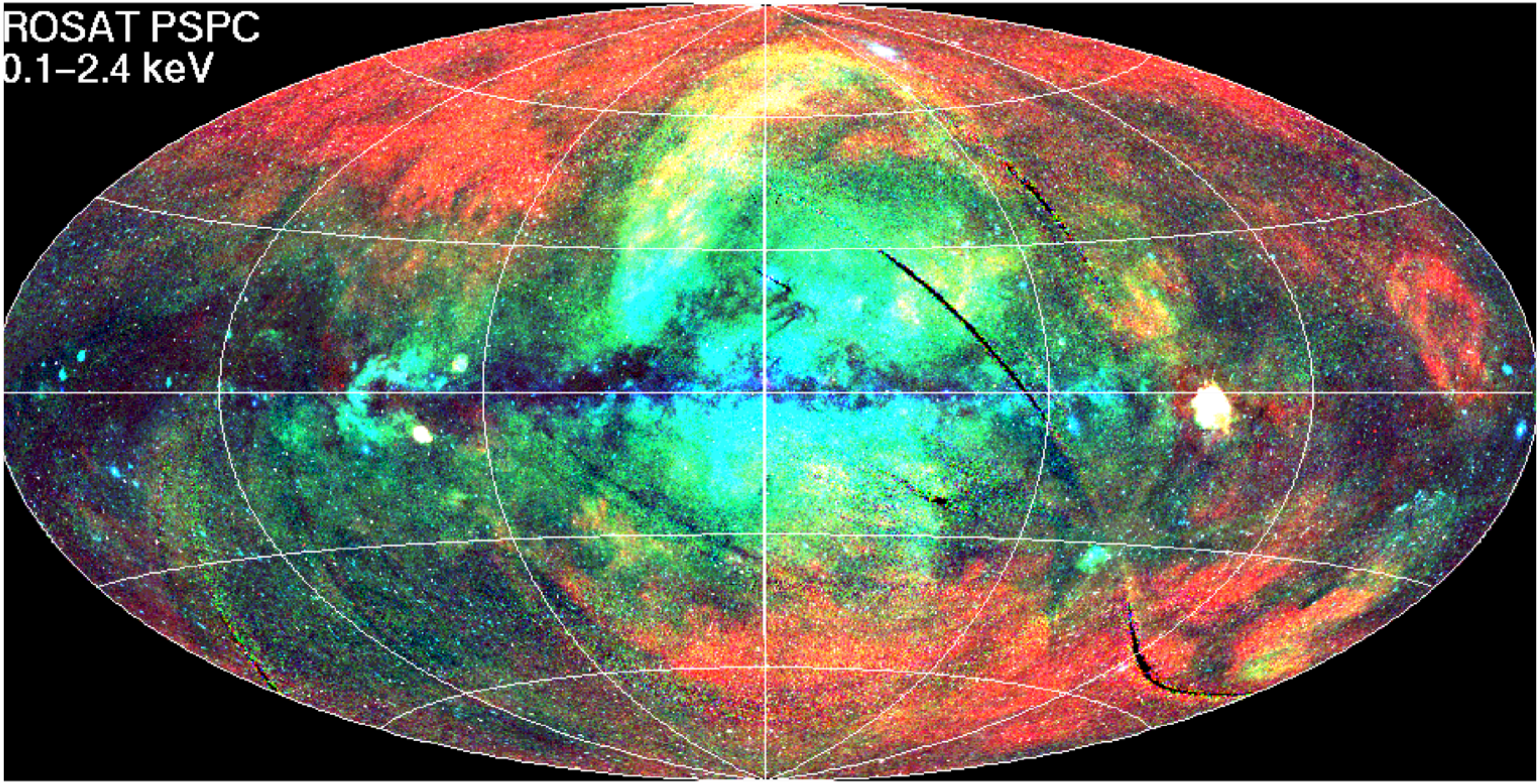
“Non-thermal” Universe

radio band



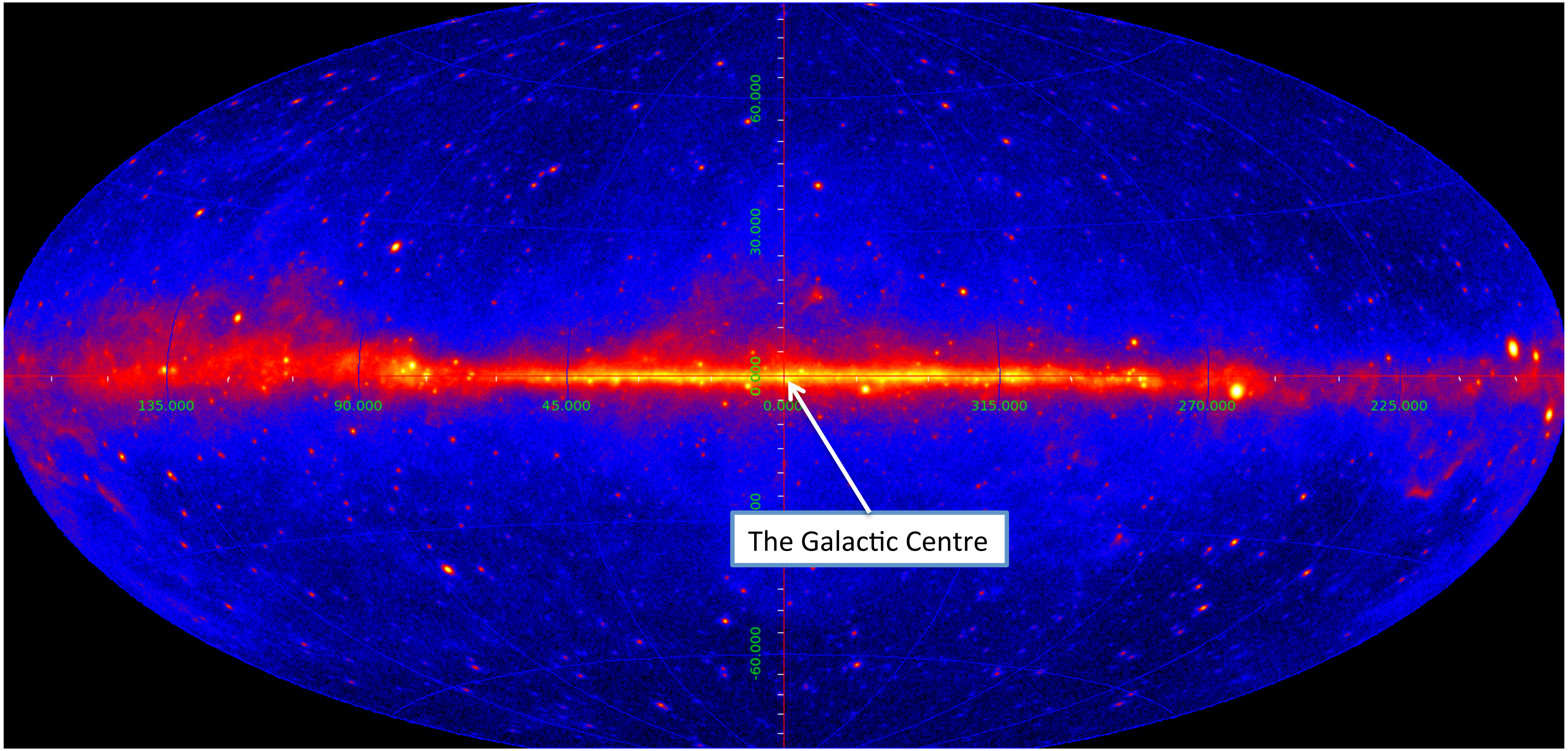
“Non-thermal” Universe

X-ray band

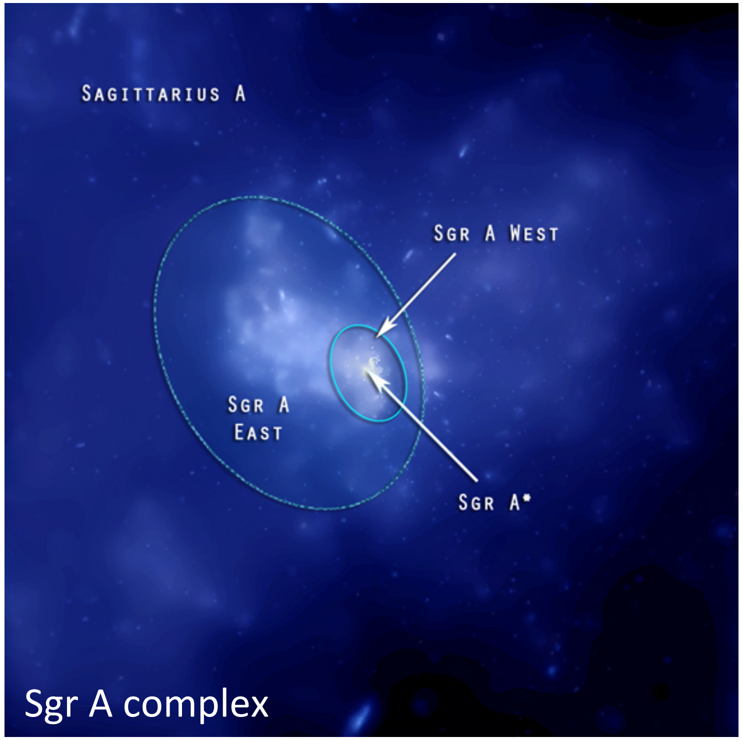


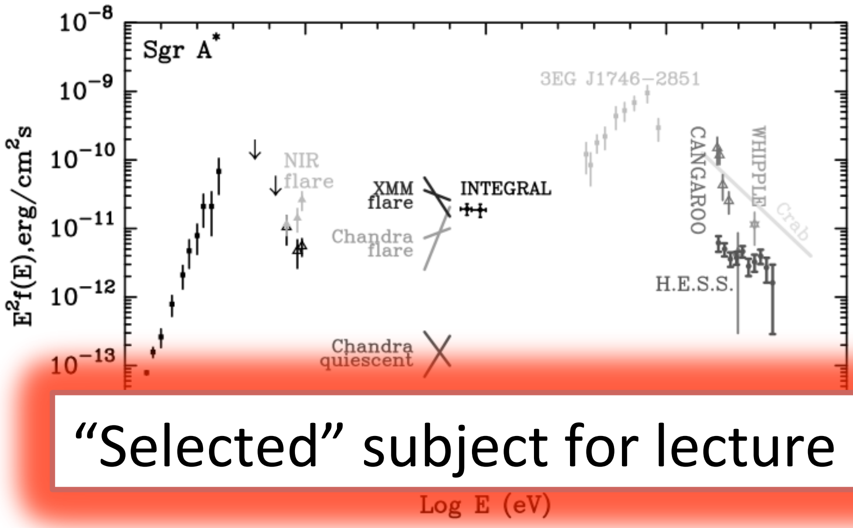
“Non-thermal” Universe

High-energy gamma-ray band



“Non-thermal” Universe





“Selected” subject for lecture 3

The **center of the Milky Way** hosts a “non-thermal” source *Sgr A** conventionally associated with a supermassive black hole with $M\approx 4\times 10^6\, M_{sun}$. The black hole powered source is embedded into an extended “bubble like” structure, *Sgr A East*, presumably a remnant of supernova explosion.

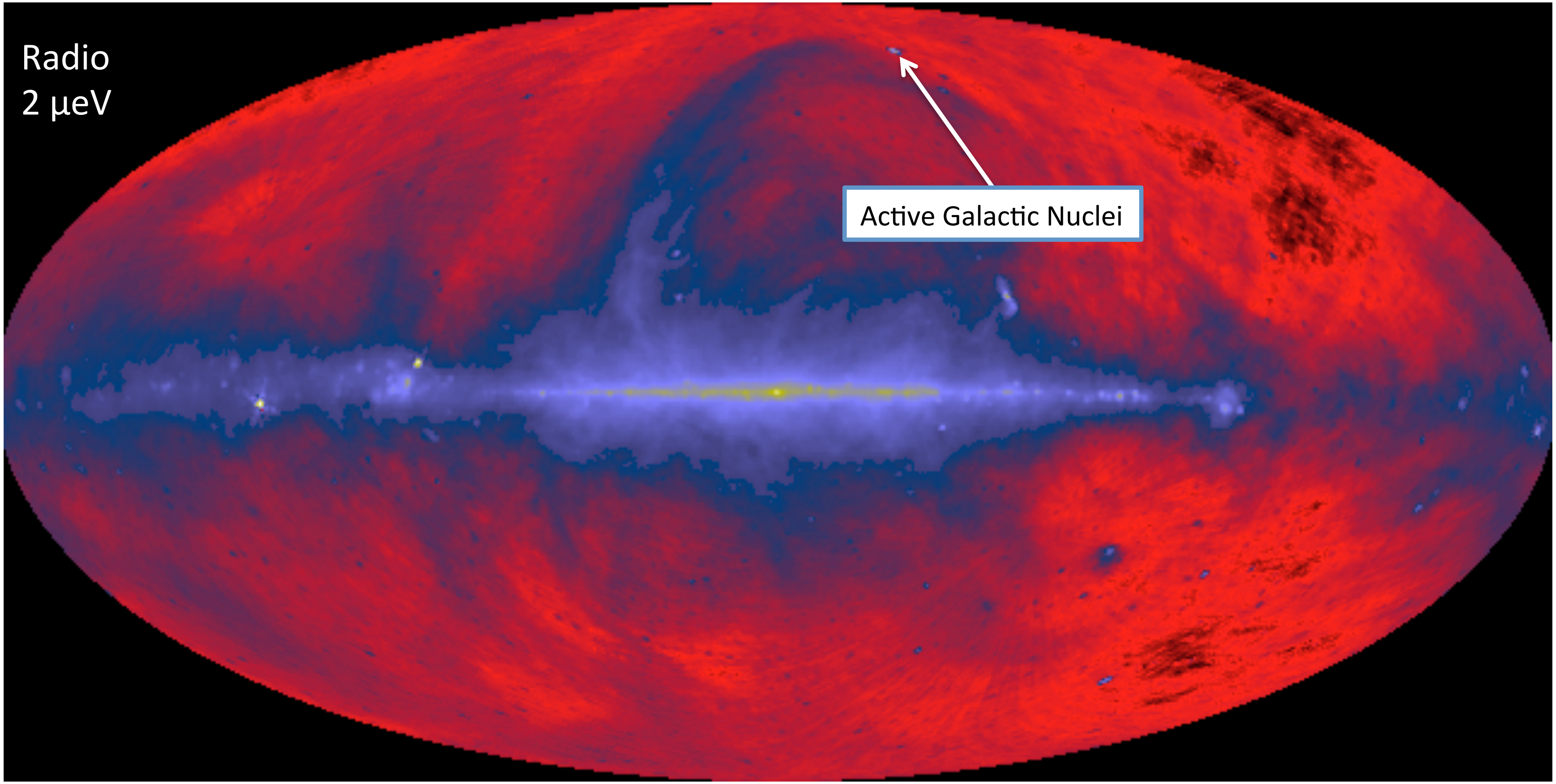
Supermassive black hole in the center of our Galaxy is currently “inactive”: its overall luminosity is about 10^{36} erg/s, which is just about 1% of typical luminosity of a massive star.

Contrary to stars, the spectrum of the supermassive black hole extends from radio to gamma-rays.

The Galactic Centre is occasionally also the largest nearby concentration of DM. Non-thermal emission from the supermassive black hole and from the extended structure around it provides an irreducible background for the search of DM signal in any energy band, from radio to gamma-rays.

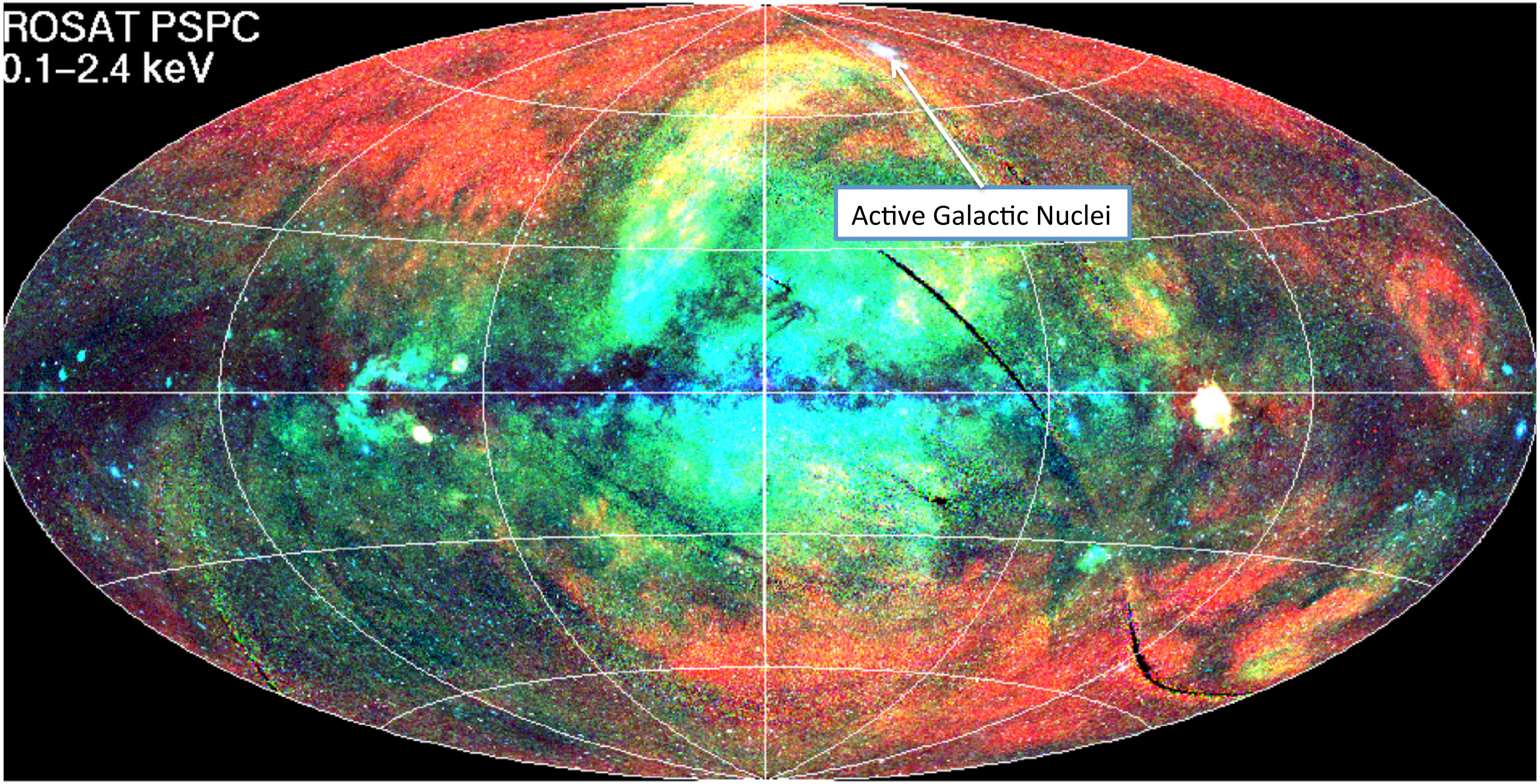
“Non-thermal” Universe

radio band



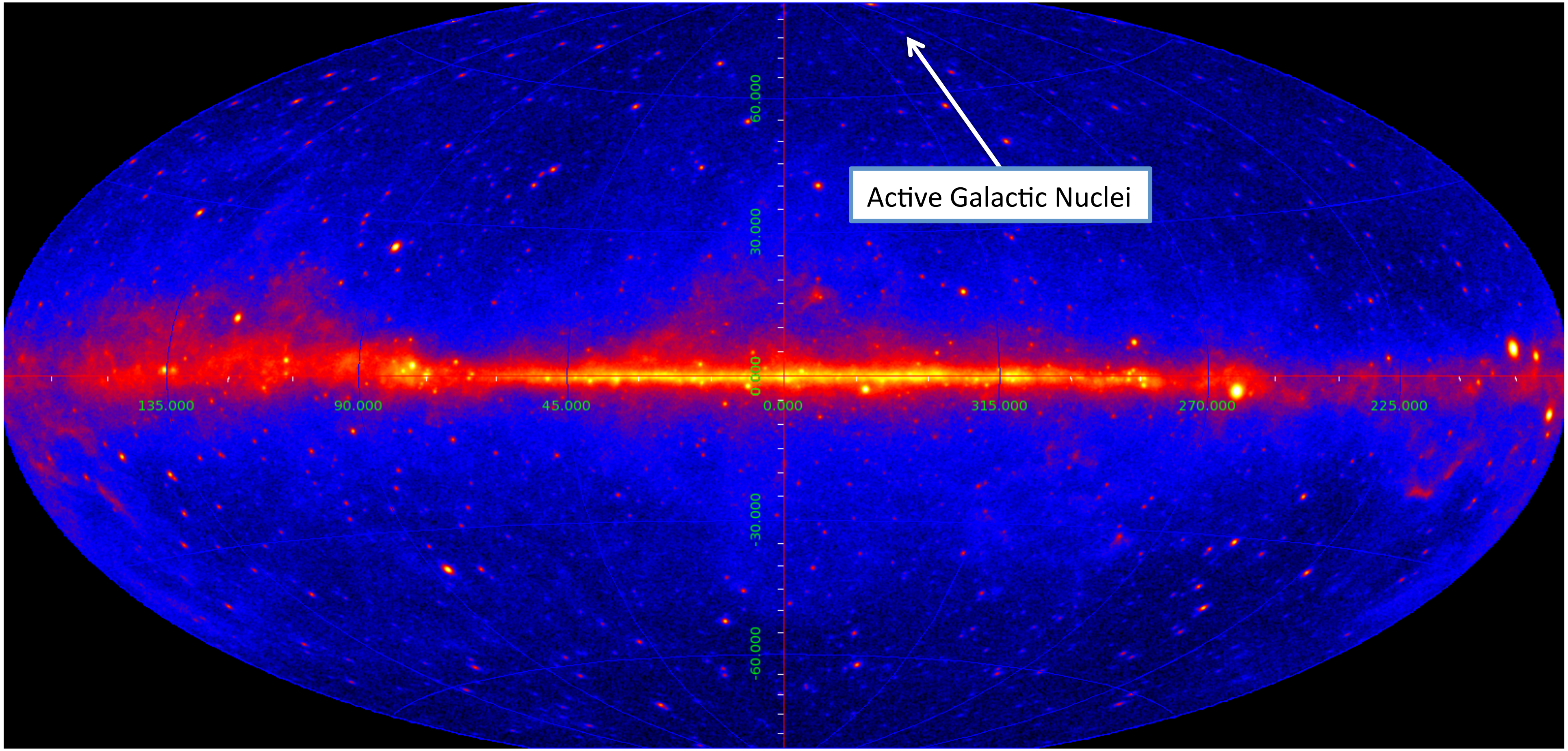
“Non-thermal” Universe

X-ray band

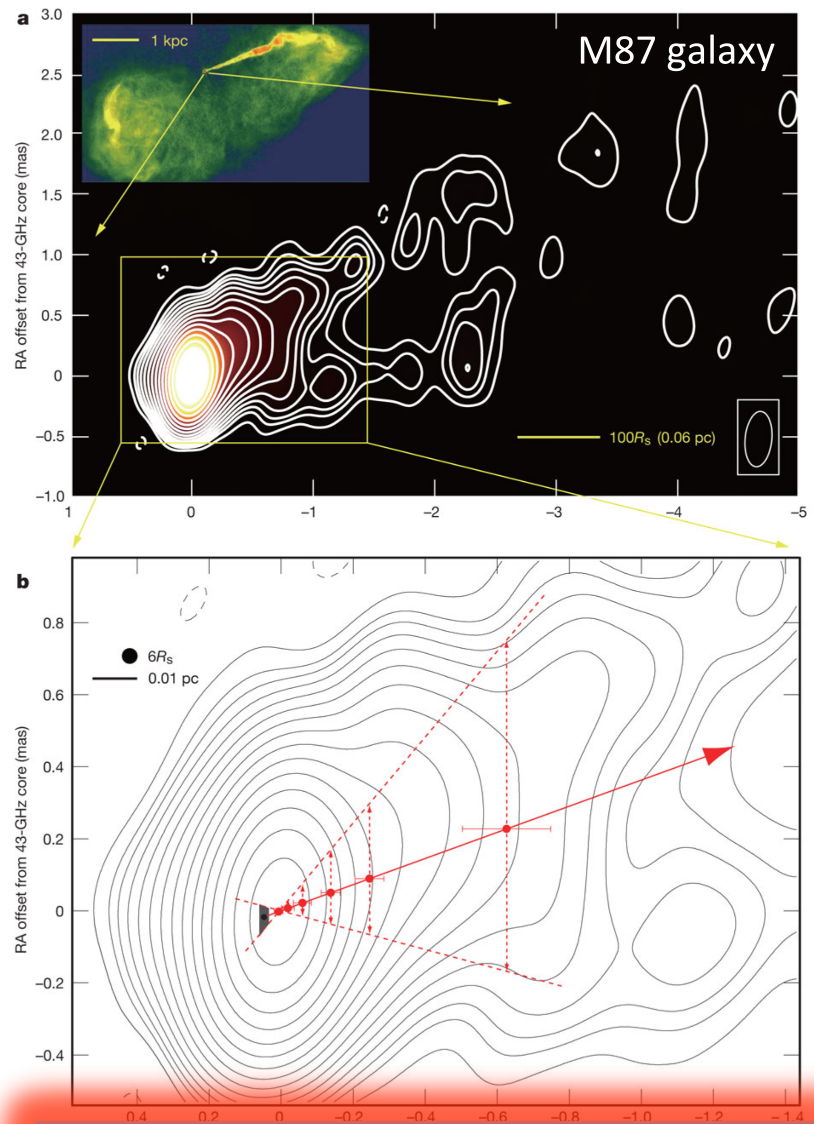


“Non-thermal” Universe

High-energy gamma-ray band



Active Galactic Nuclei



Active Galactic Nuclei (AGN) are sources powered by "active" supermassive black holes in the centres of galaxies.

Two types of active supermassive black holes are known: (a) "radio quiet" AGN, emitting thermal radiation from the accretion flow and (b) "radio loud" AGN producing spectacular phenomenon of large scale jets.

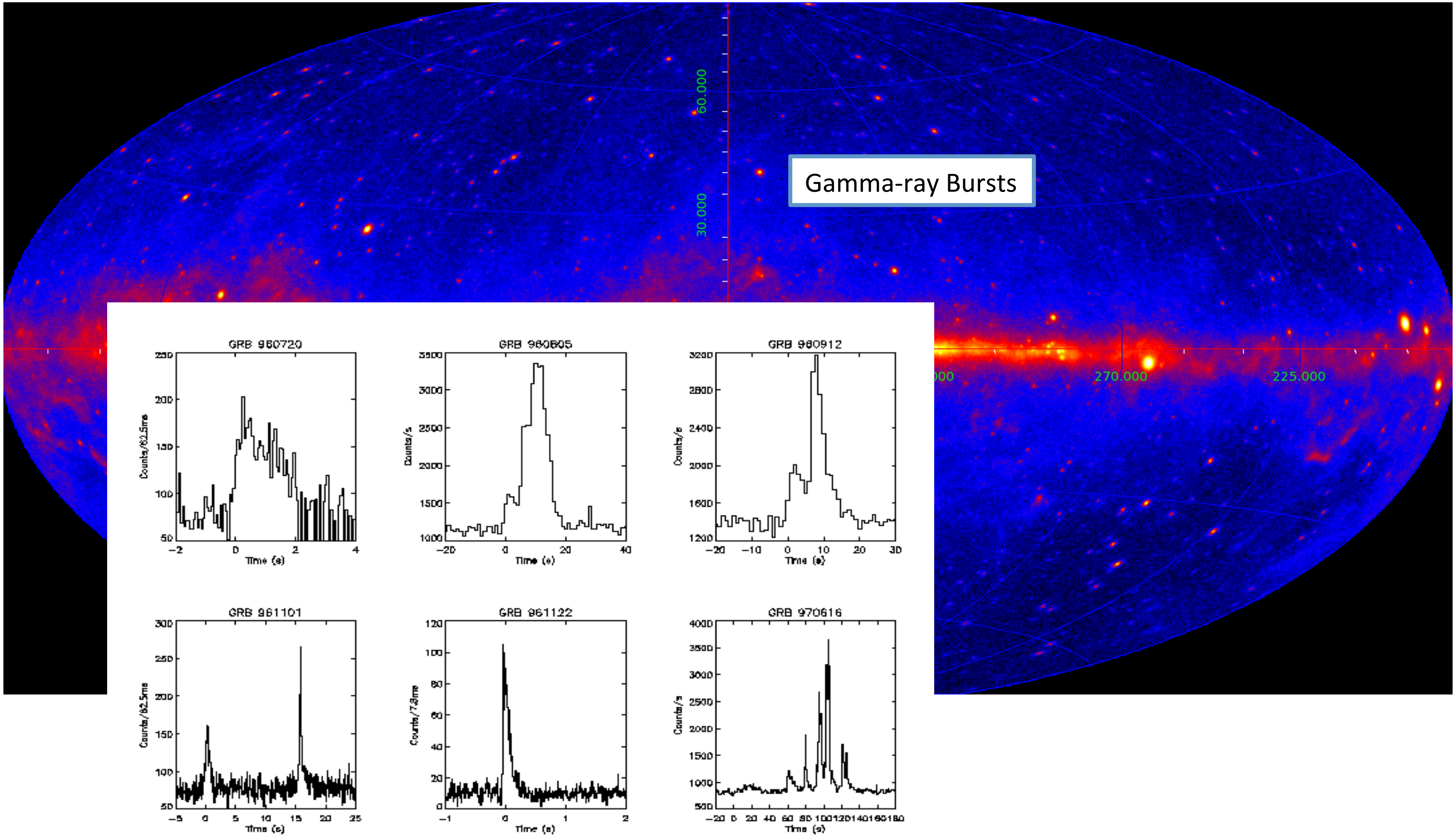
Spectra of emission from radio loud AGN stretch from radio to gamma-rays and are formed by **synchrotron and inverse Compton** emission from high-energy electrons.

Radio loud AGN often reside in the centres of galaxy clusters. They produce radio-to-gamma-ray emission which serves as background for the search of DM decay / annihilation signal from these large DM concentrations.

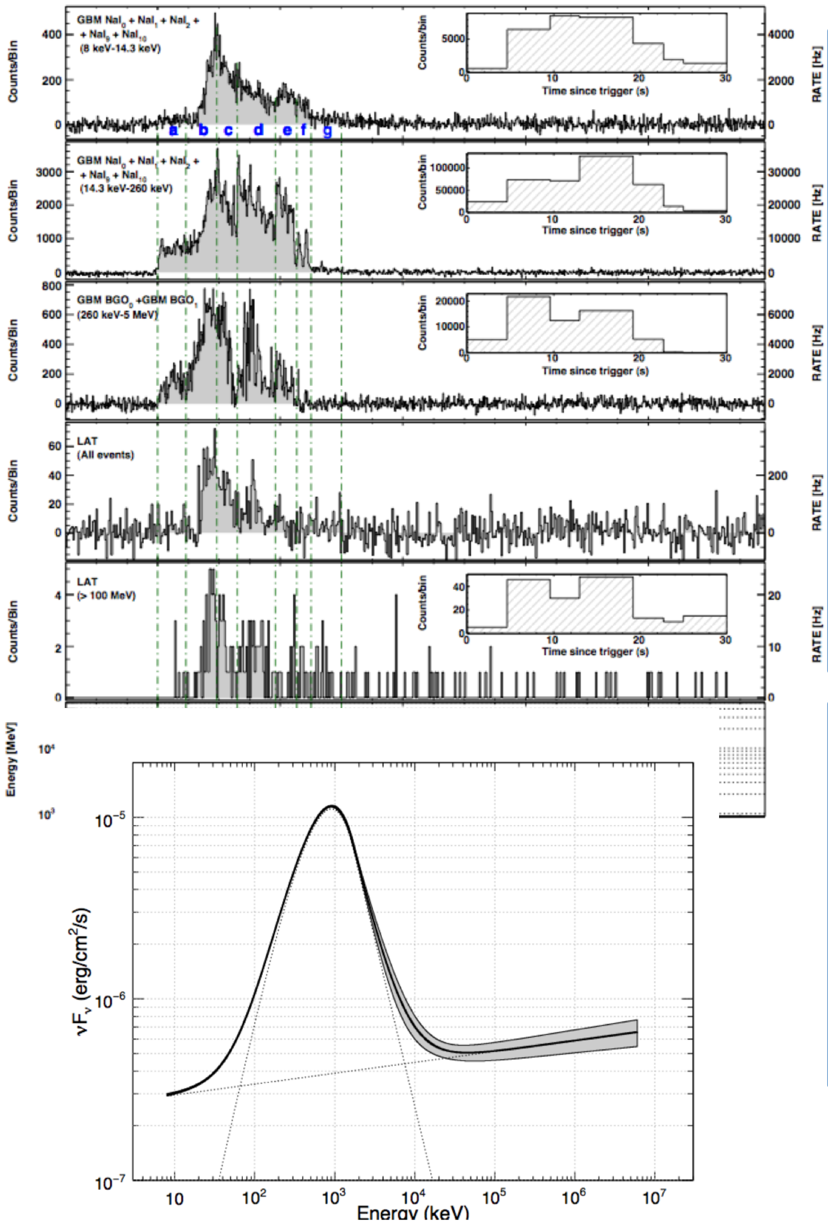
"Selected" subject for lecture 3

“Non-thermal” Universe

High-energy gamma-ray band



Gamma-ray Bursts



Gamma-ray bursts (GRB) are explosive events of duration from <0.1 s to $>10^3$ s, appearing as short flashes of gamma-ray flux from random directions on the sky.

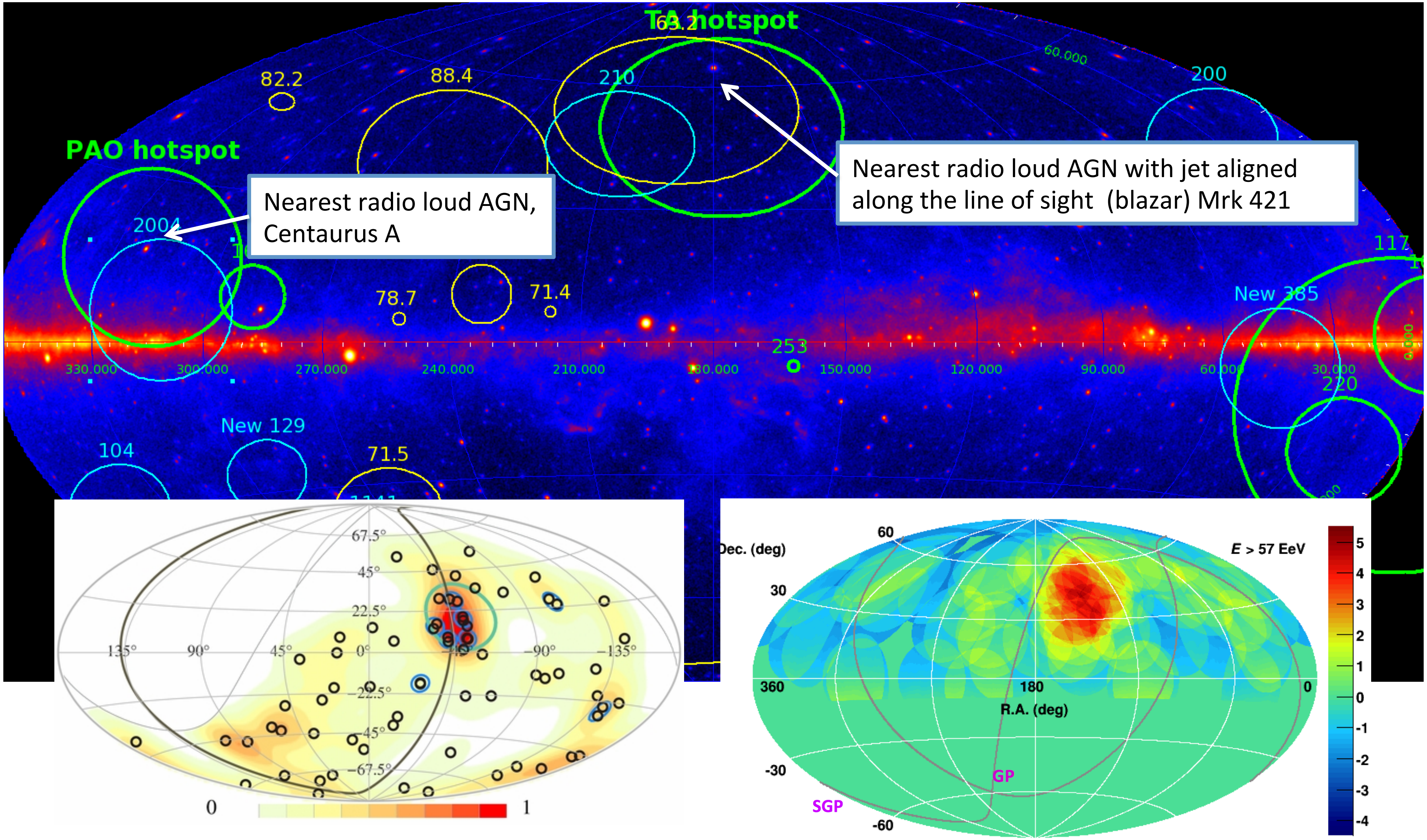
Longer GRBs are most probably the results of particle acceleration events at the moment of gravitational collapse of massive stars.

Origin of short GRBs is unsure. The main hypothesis is that they are by-products of merger events of binary neutron stars and/or black holes.

Broad band spectrum of emission from the GRBs is dominated by the energy output either in the MeV or in the multi-GeV energy range. The spectrum stretches from radio to the highest energy gamma-ray band. Physical mechanisms of generation of different emission components are not well constrained.

“Non-thermal” Universe in Multi-Messenger picture

Very High-Energy neutrinos + gamma-rays + Ultra-High-Energy cosmic rays



IceCube Collab ‘13,’14; Pierre Auger Collab. ‘11, TA Collab. ‘14

Summary

High-energy and Multi-wavelength sky has contributions from *thermal* and *non-thermal* source populations.

Thermal sources are

– *normal stars* in the **infrared / visible /UV** band,
– *molecular gas and dust* in the **far / near infrared** band,
– *X-ray binary systems* powered by accretion,
supernova remnants heated by the mechanical energy released in supernova explosions,
galaxy clusters heated by the release of gravitational energy as well as
interstellar medium of star-forming galaxies heated by star formation / supernovae activity in the **X-ray** band.

Non-Thermal sources are

– *interstellar medium of galaxies*
– *supernova remnants*,
– *pulsars and pulsar wind nebulae*,
–*Gamma-Ray Bursts*,
– *Active Galactic Nuclei*, with all sources visible across energy bands, from **radio to gamma-rays** and possibly also in very-high-energy neutrinos and some of them in ultra-high-energy cosmic rays.

The non-thermal emission is the result of interactions and radiative losses of high-energy particles, with **synchrotron, inverse Compton and Bremsstrahlung** being the main radiative processes for high-energy electrons and **pion production and decay** being the main radiative process for high-energy protons and nuclei.