Astrophysical background
Episode I – the origin

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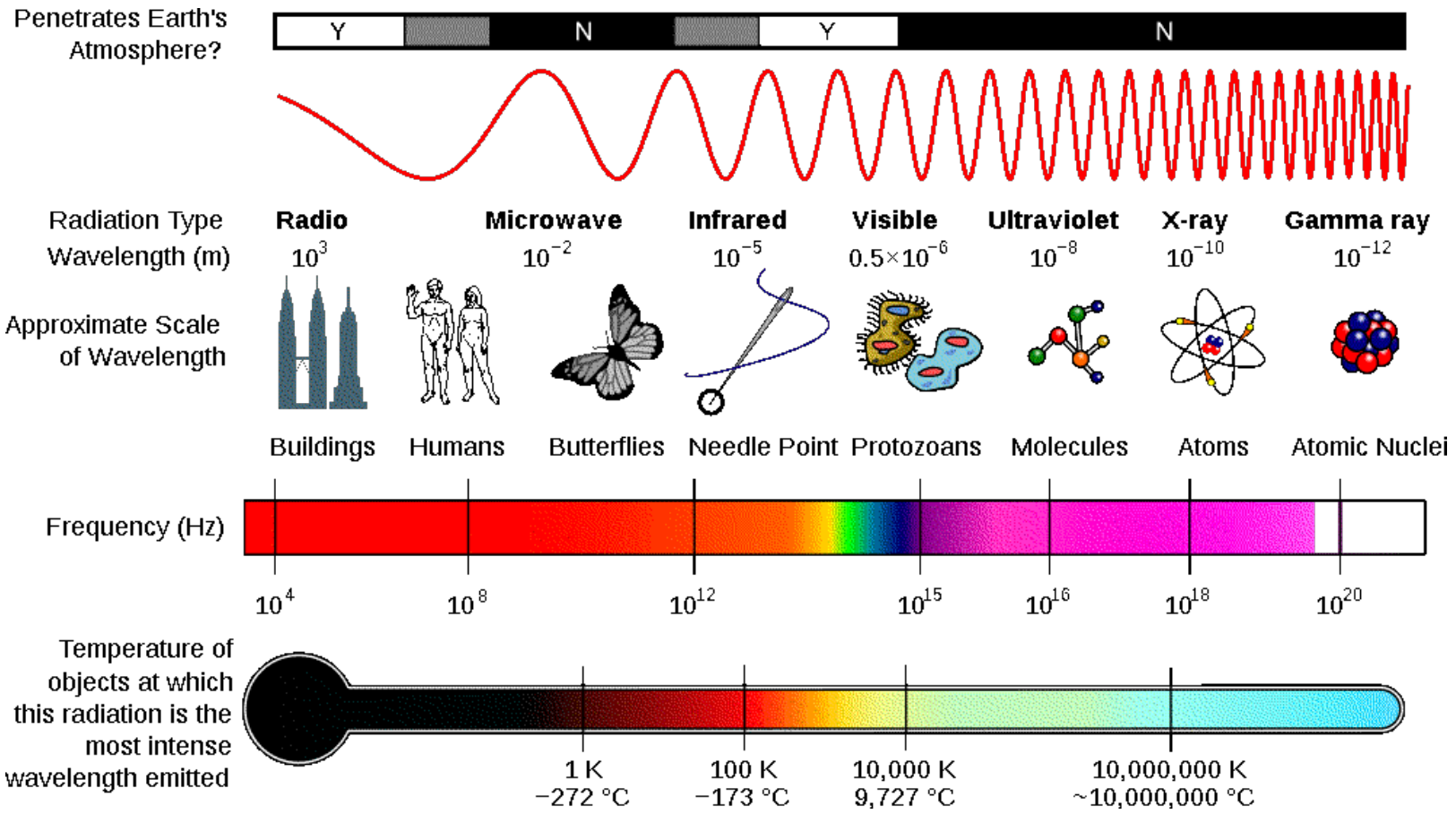
Chiang Mai (Thailand) 19/02/2019

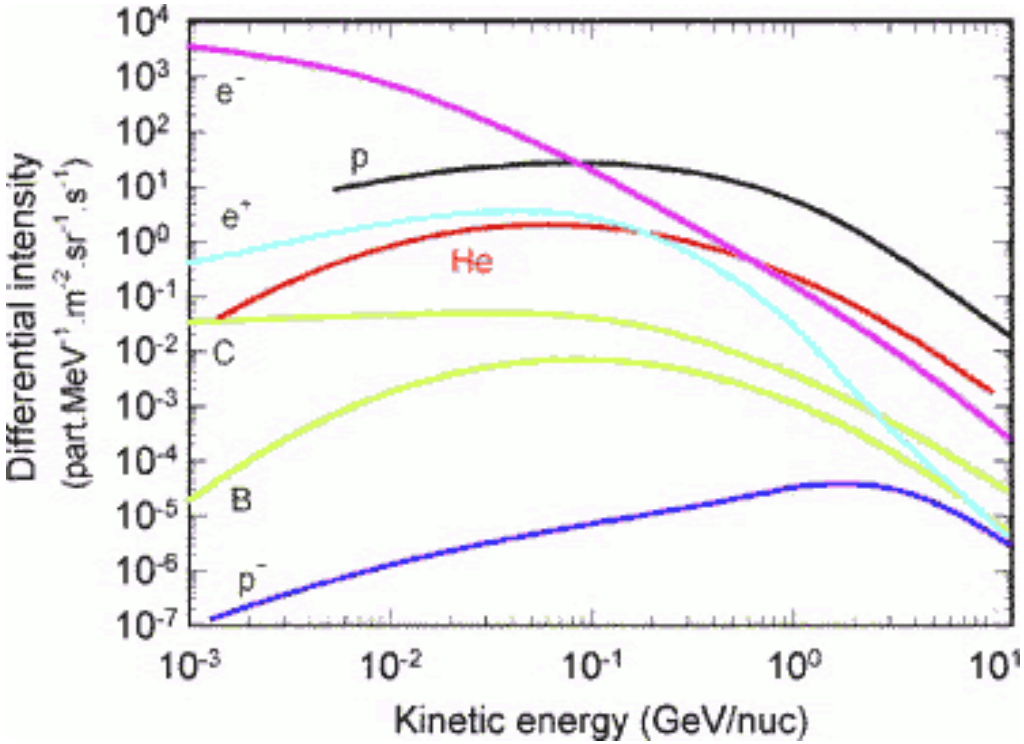
Outline

Thermal processes



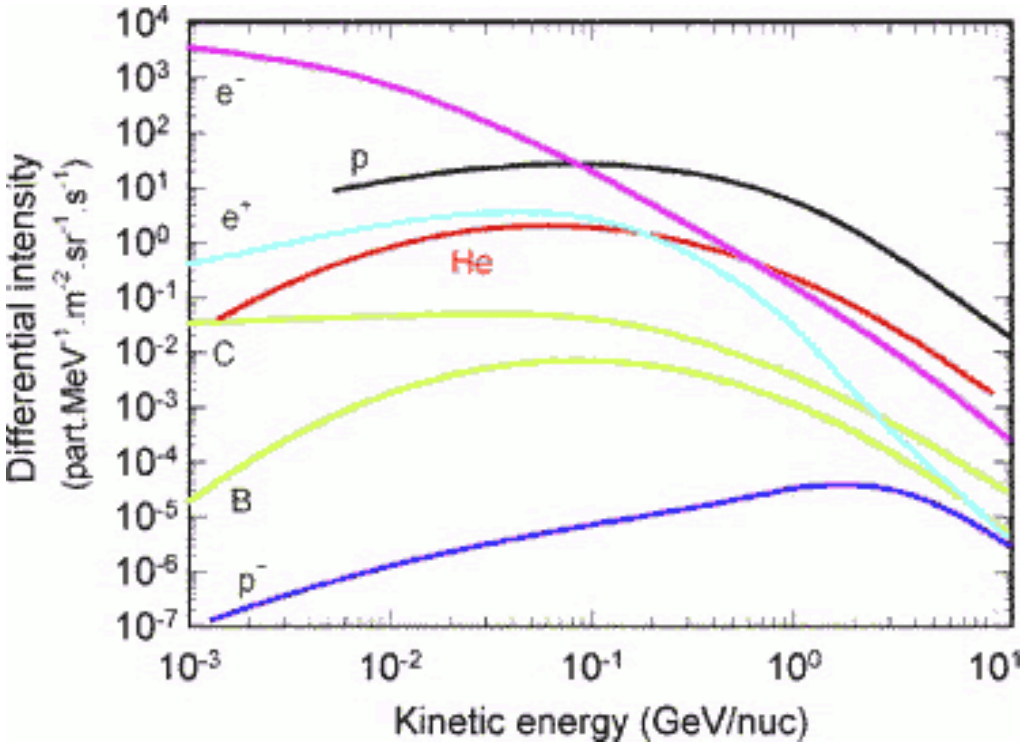
$$1\ \mathrm{eV} \sim h\,(10^5\ \mathrm{GHz}) \sim \frac{hc}{10^4\ \text{Å}} \sim \frac{hc}{1\ \mu m} \sim \frac{3}{2}k\,(8000\ \mathrm{K}) \sim \frac{m_p\,(14\ \mathrm{km/s})^2}{2}$$

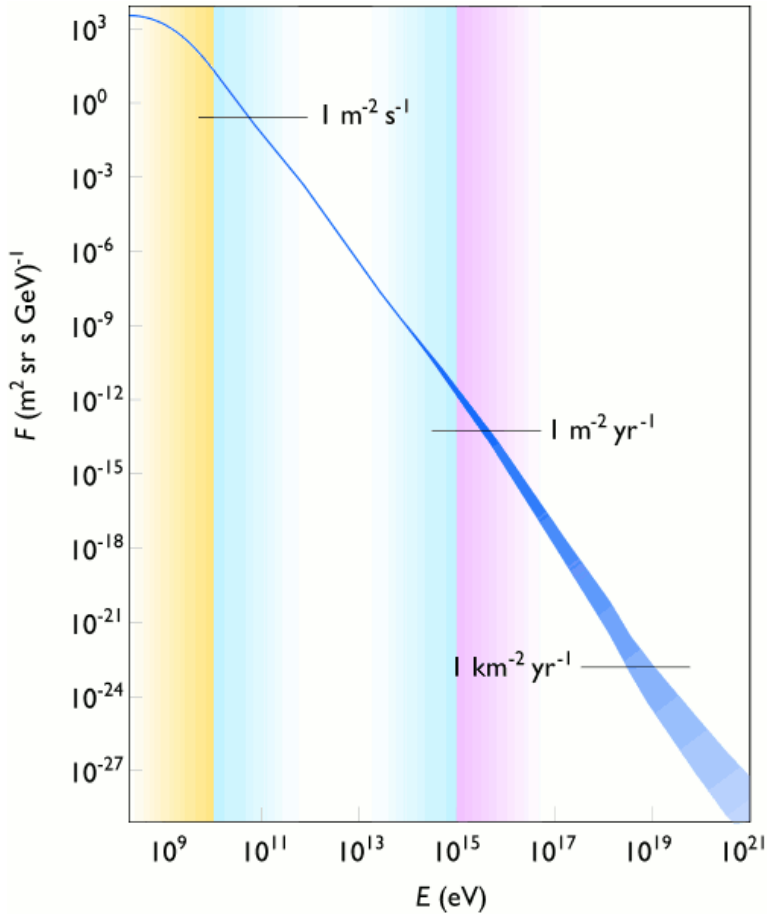
Cosmic rays

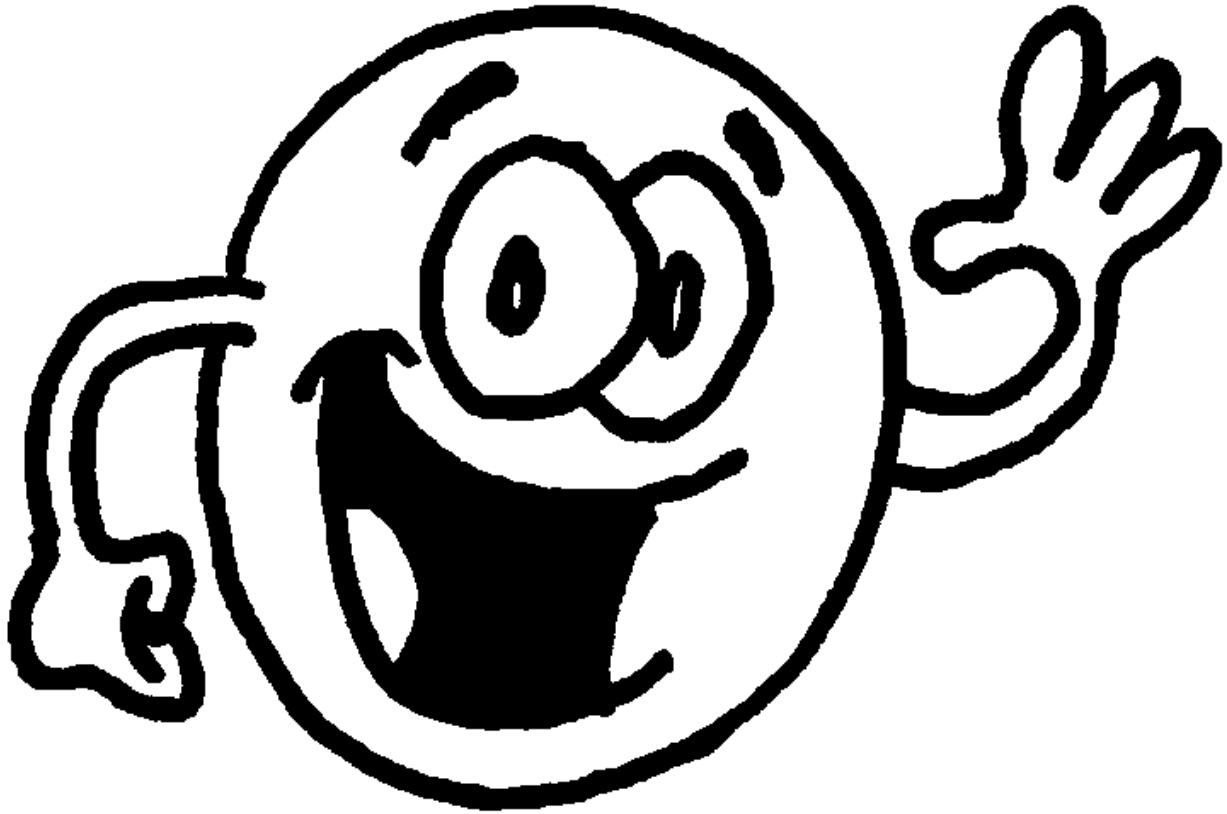


- Protons: 88 %
- Helium: 10 %
- Other nuclei: 1 %
- Electrons: 1 %

Cosmic rays

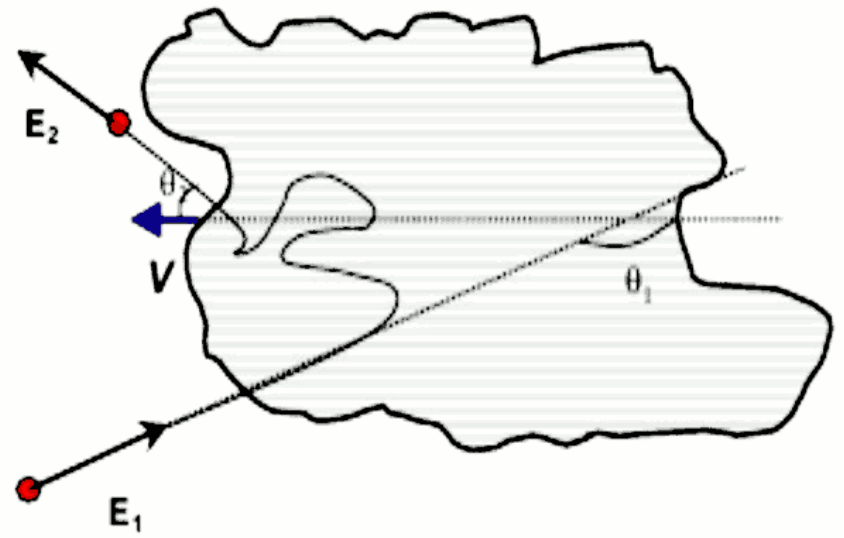

Differential intensity
(part.MeV^{-1}.m^{-2}.sr^{-1}.s^{-1})
Kinetic energy (GeV/nuc)
e$^-$
e$^+$
p
He
C
B
p$^-$

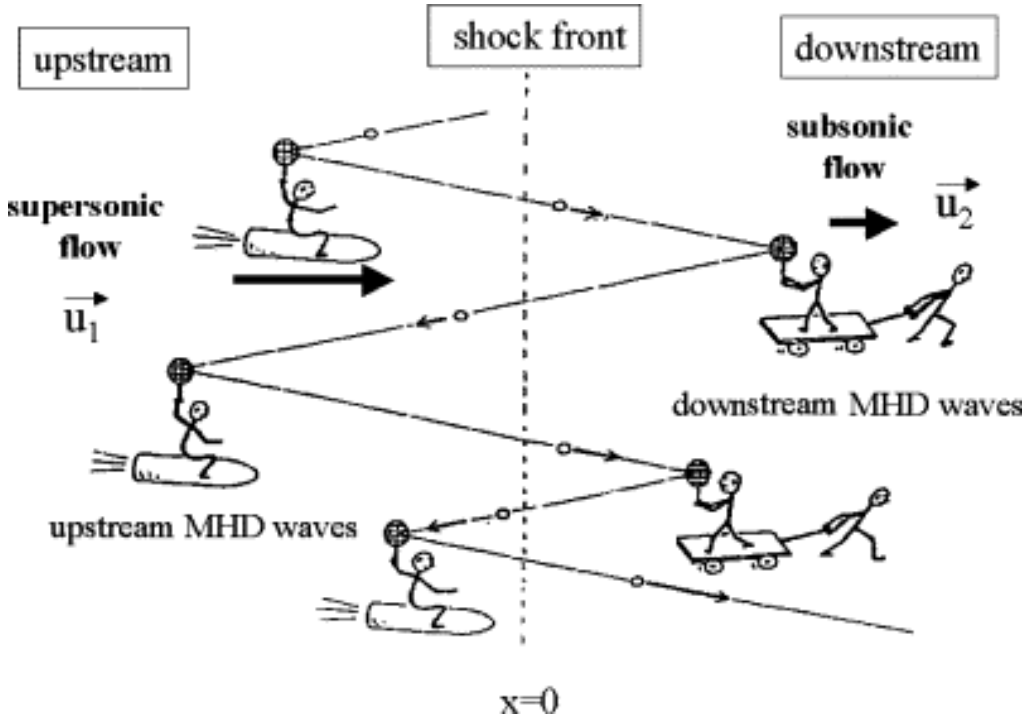

F (m^2 sr s GeV)$^{-1}$
E (eV)
1 m^{-2} s^{-1}
1 m^{-2} yr^{-1}
1 km^{-2} yr^{-1}



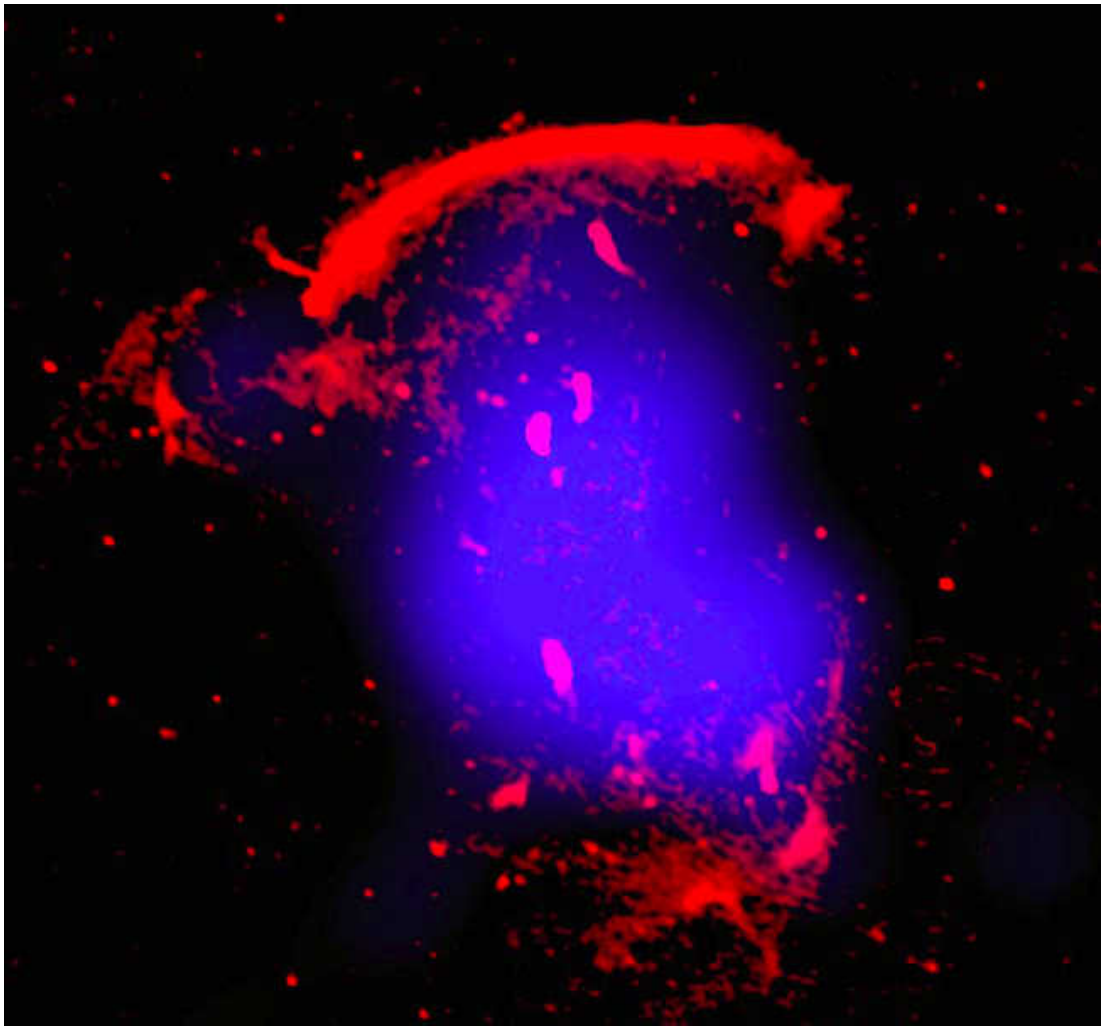
Where do the cosmic rays come from?

Fermi acceleration mechanisms

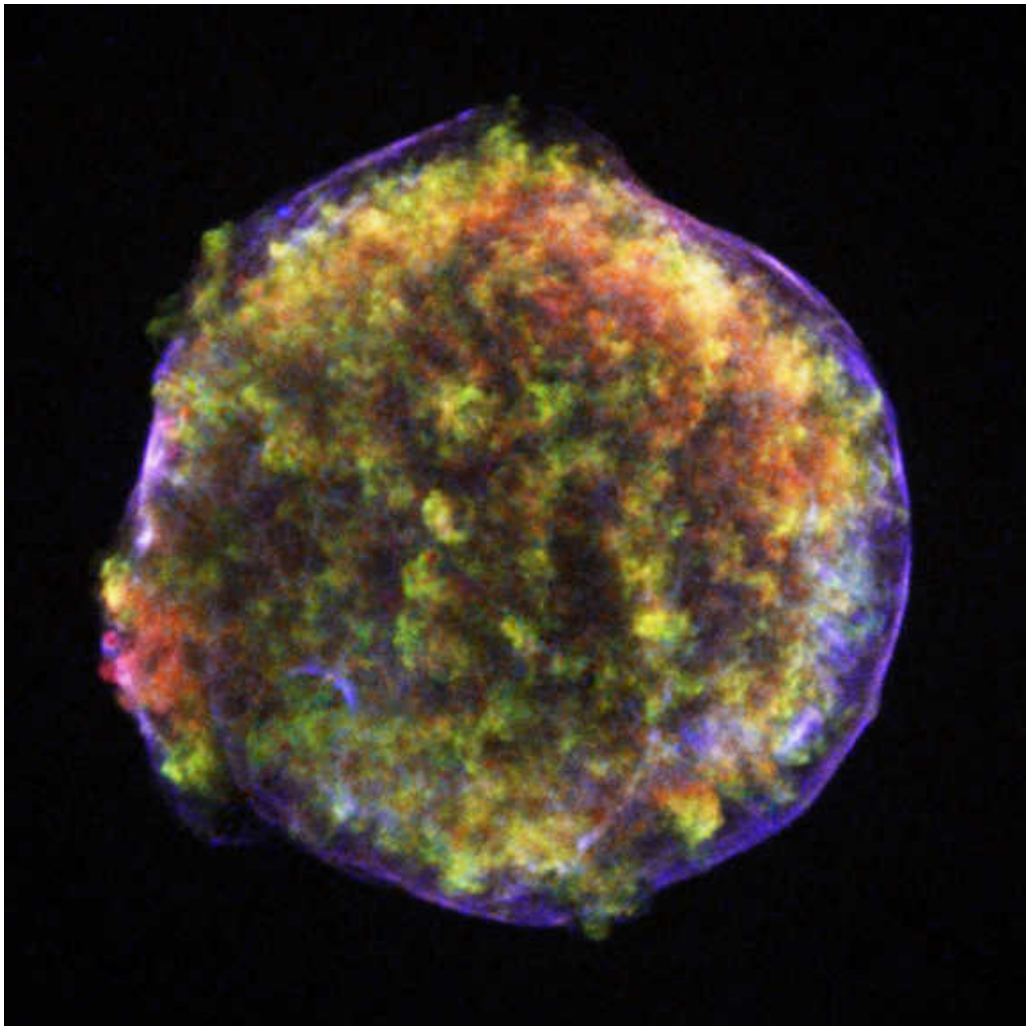




Astrophysical shocks



Supernova remnants (SNR)

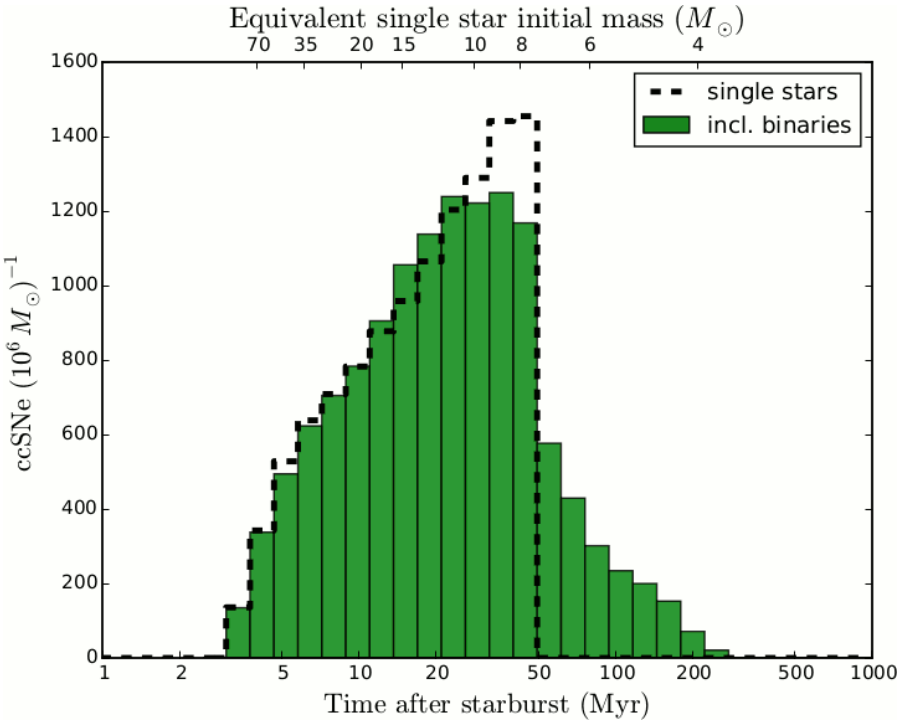


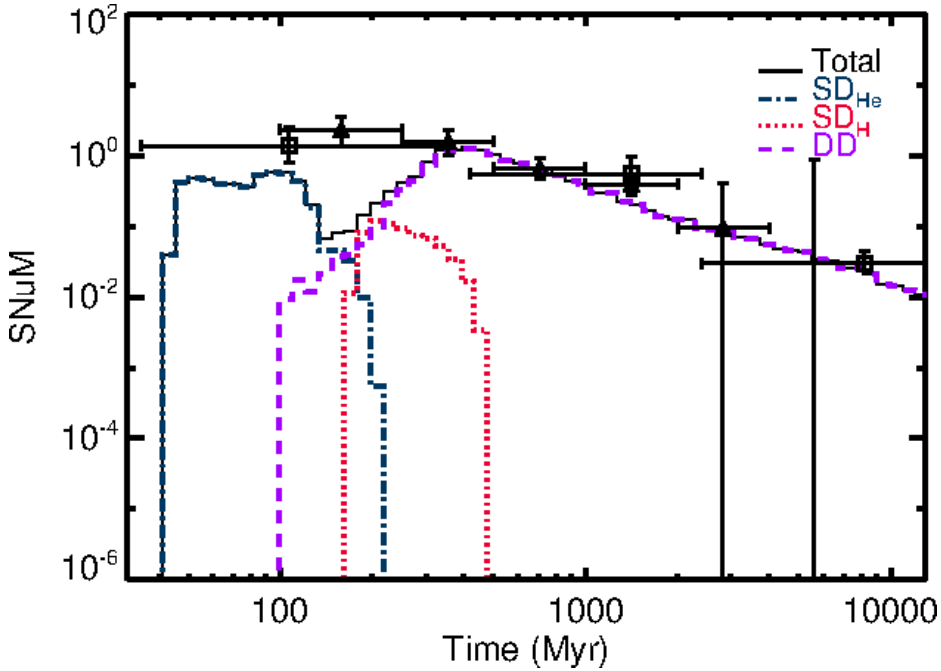
Libro del nueuo Co
META, Y DEL LV-
gar donde ſe hazẽ; y como ſe vera por las
Parallaxes quan lexos eſtan de tier-
ra; y del Prognoſtico deſte:
Compueſto por el Maeſtro Hieronymo Muñoz
Valenciano, Cathedratico de Hebreo y Mathe-
maticas en la Vniuerſidad de Valencia.

EN VALENTIA,

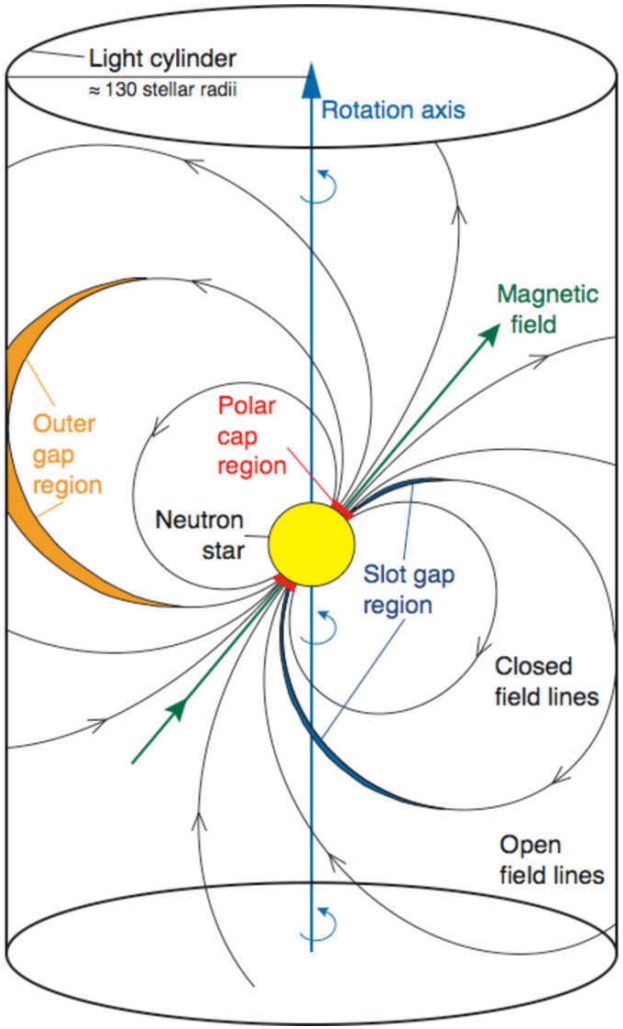
Impreſſo con licencia. en la officina de Pedro
de Huete, en la plaça de la hierba. 1573.

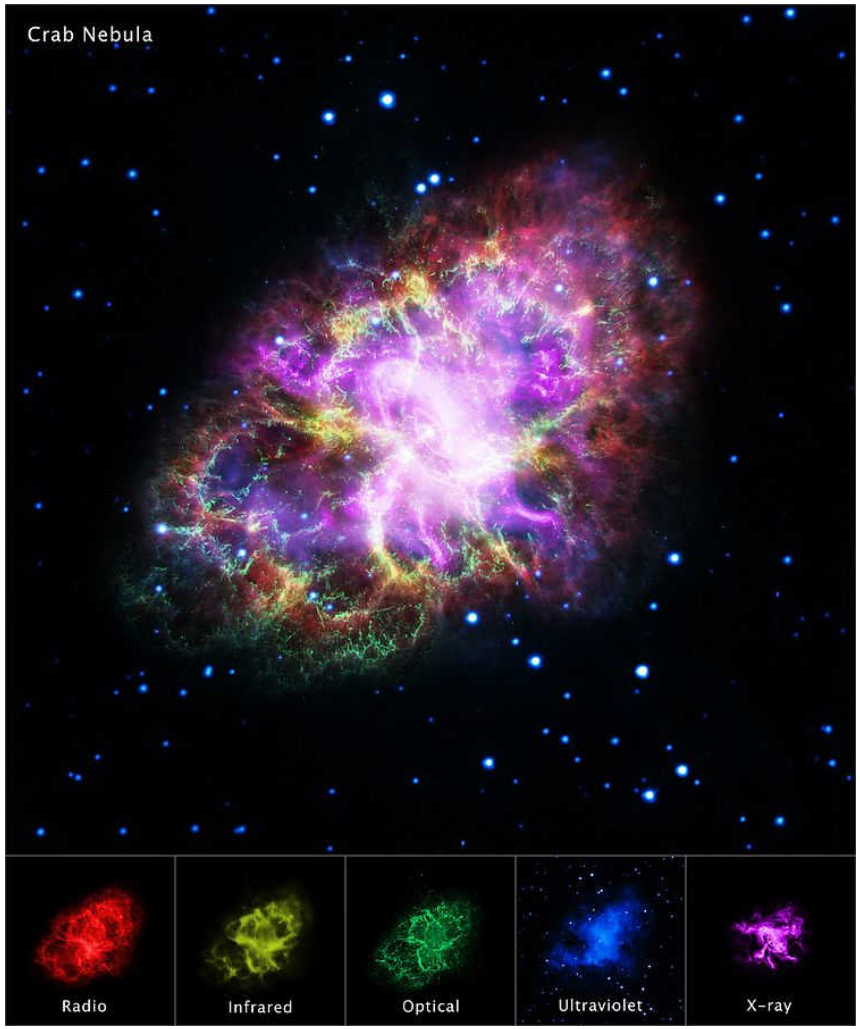
Supernova remnants (SNR)





Pulsar Wind Nebulae (PWN)





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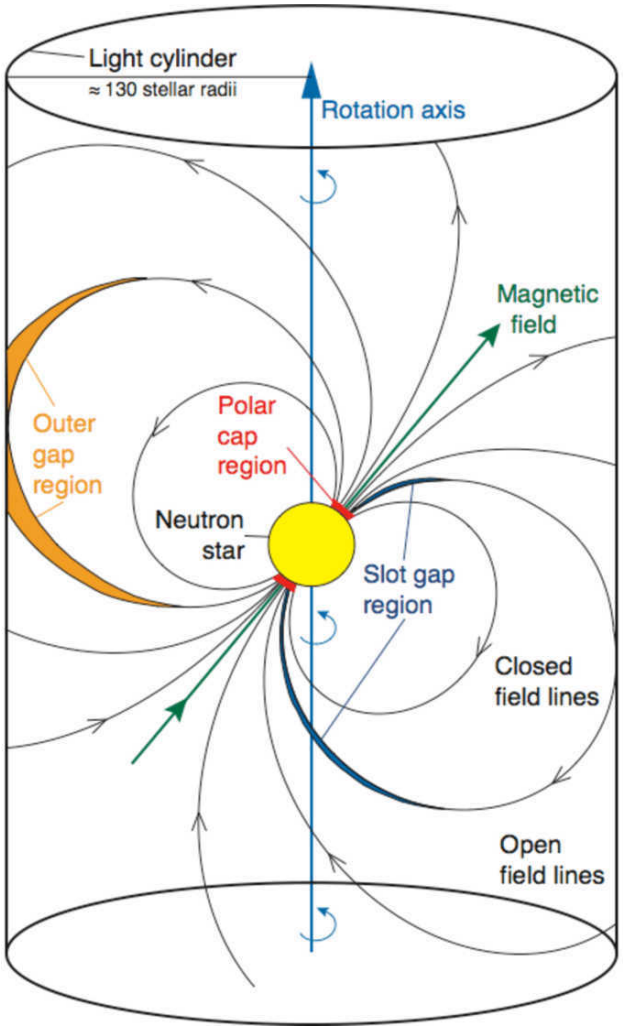
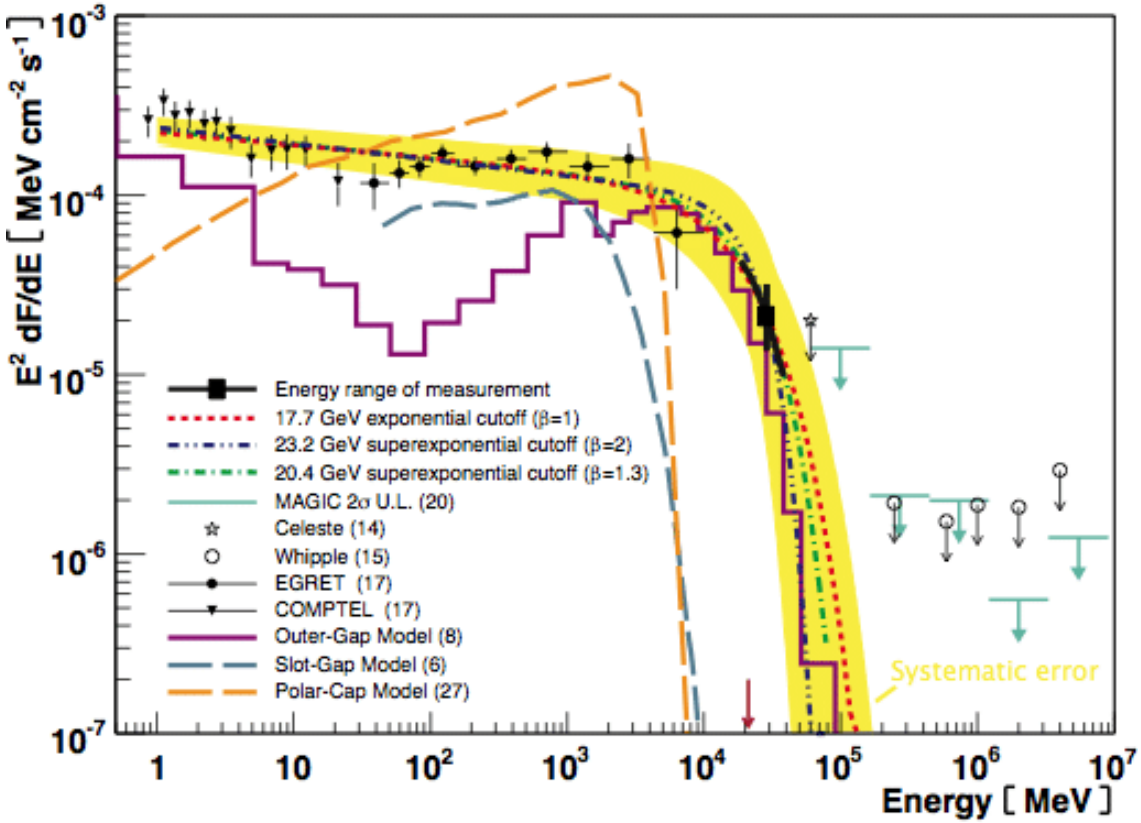
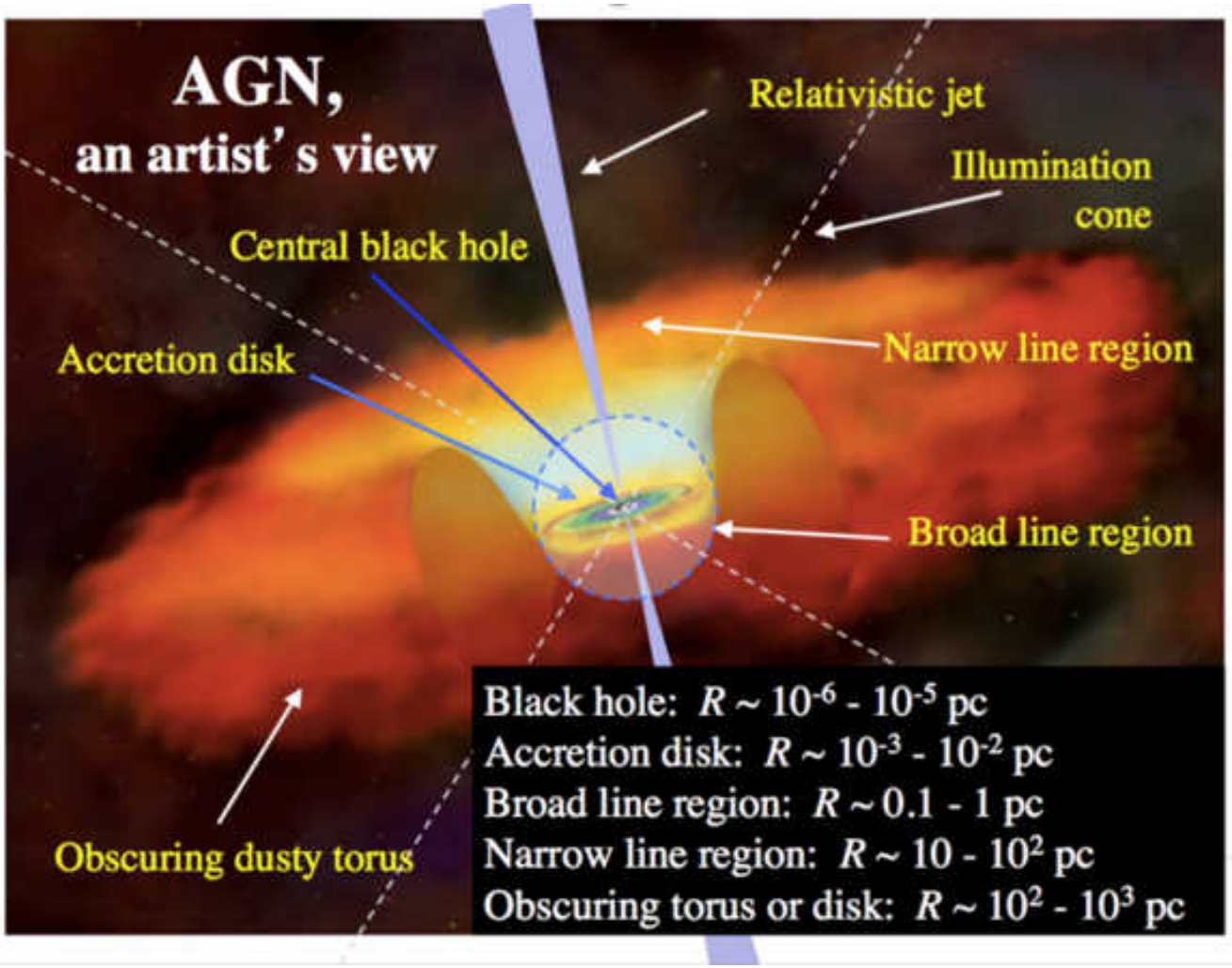




Active Galactic Nuclei (AGN)



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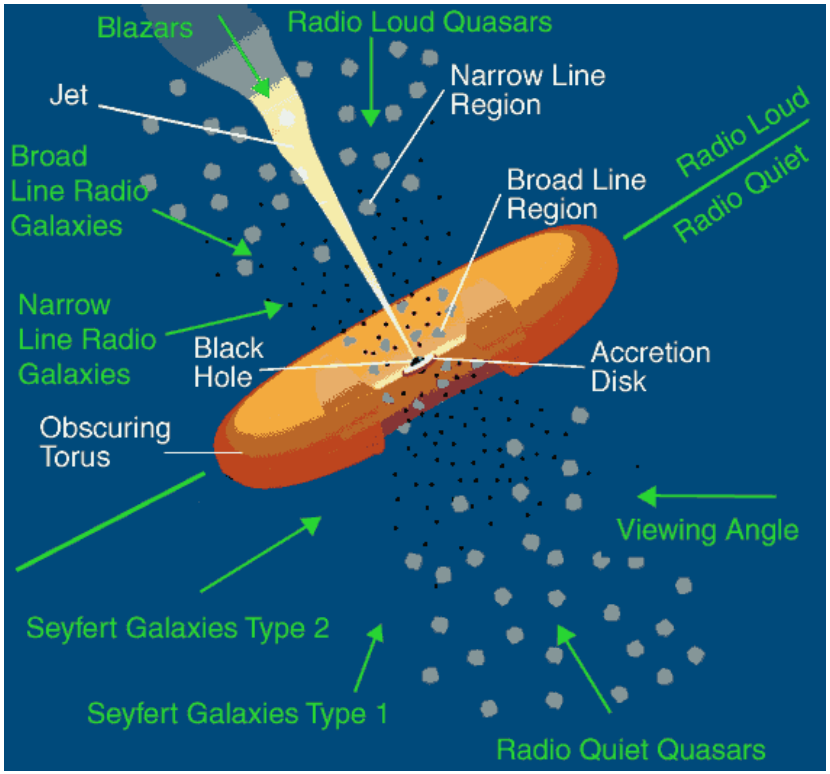

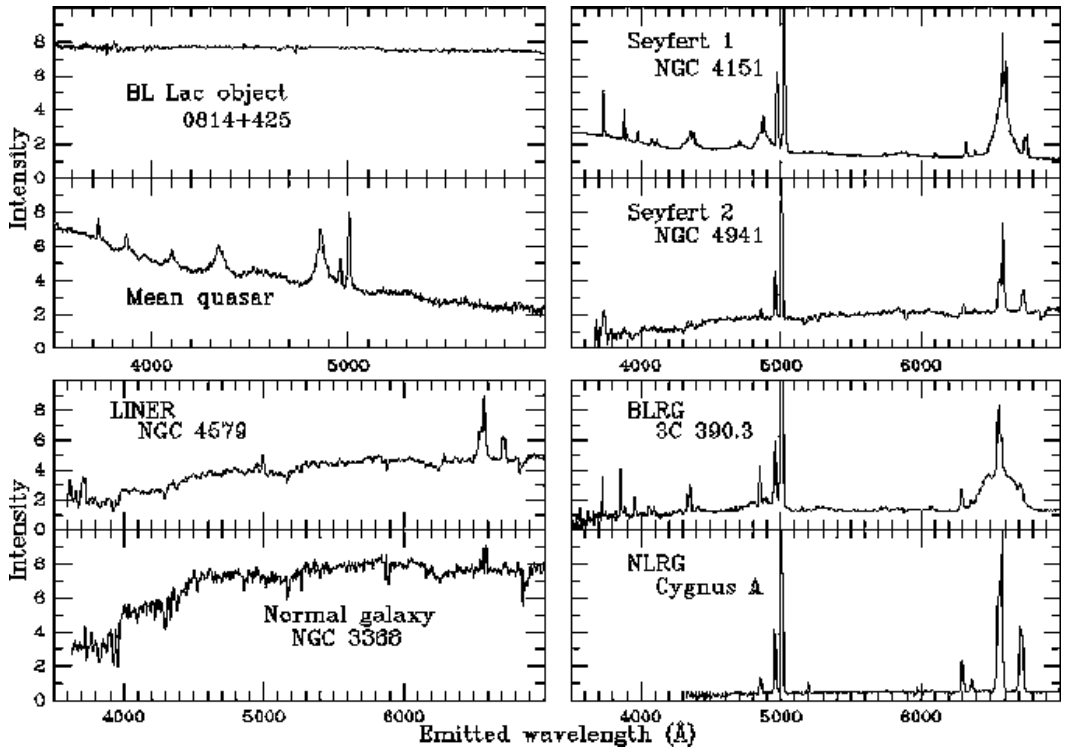

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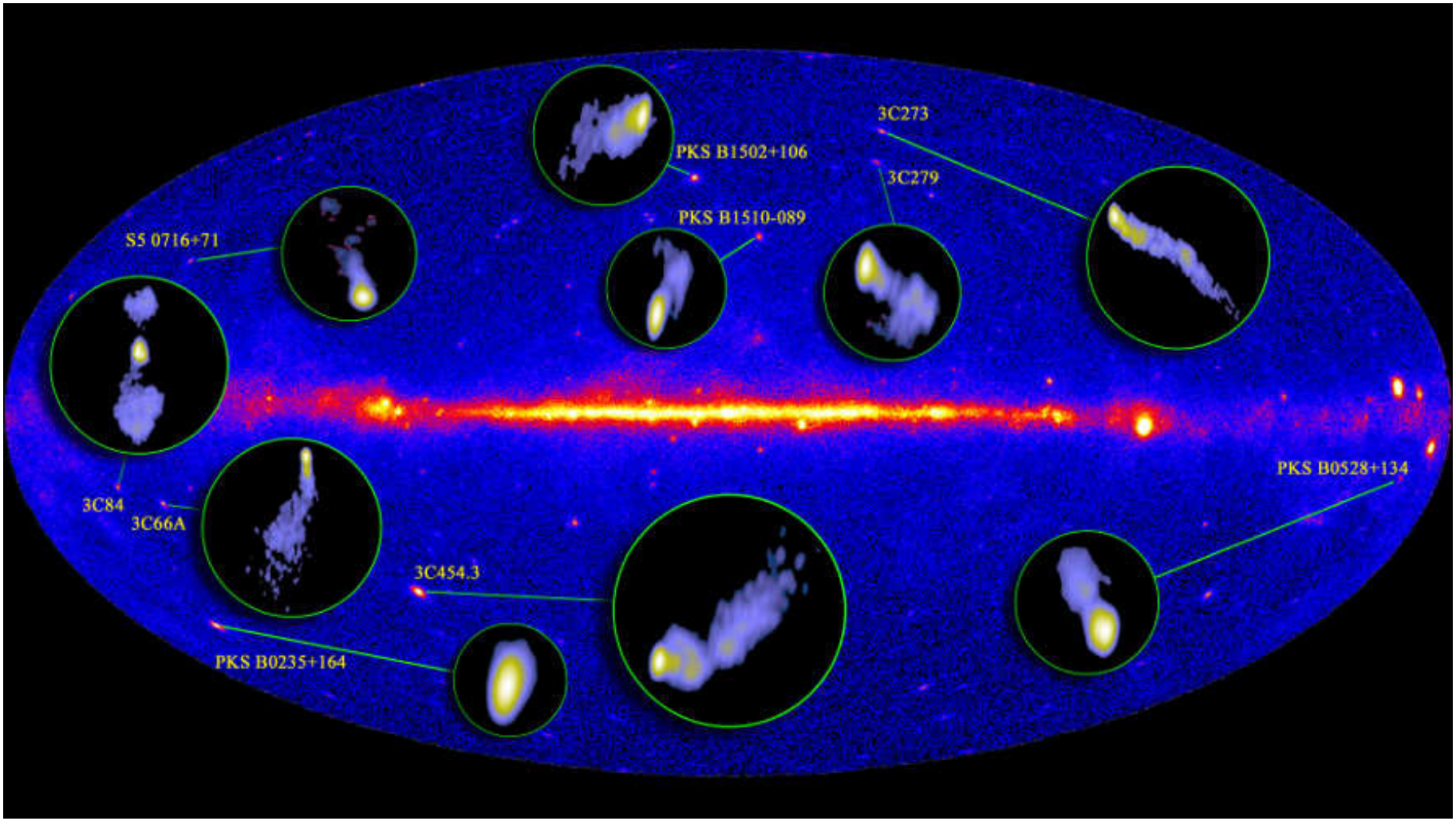
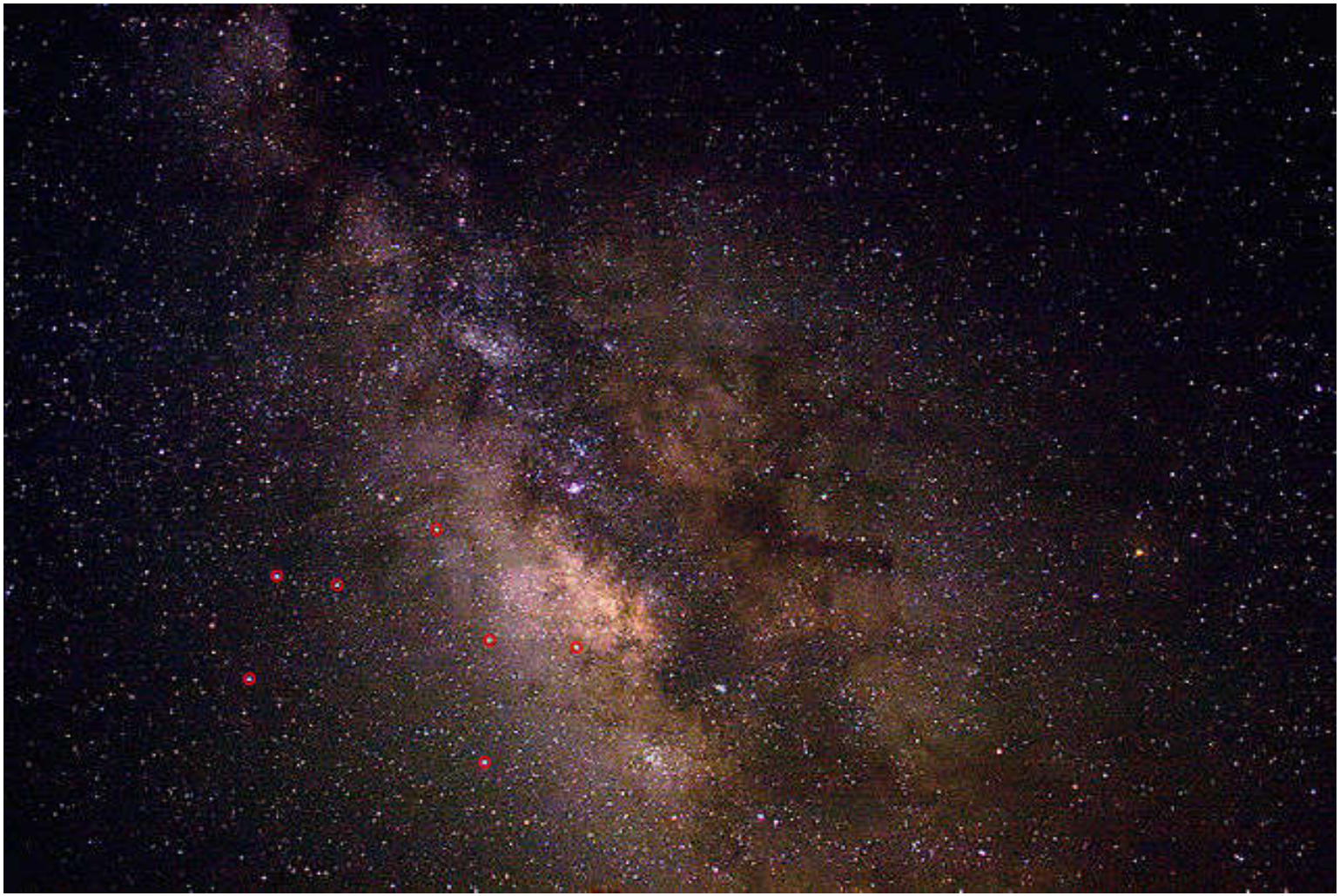
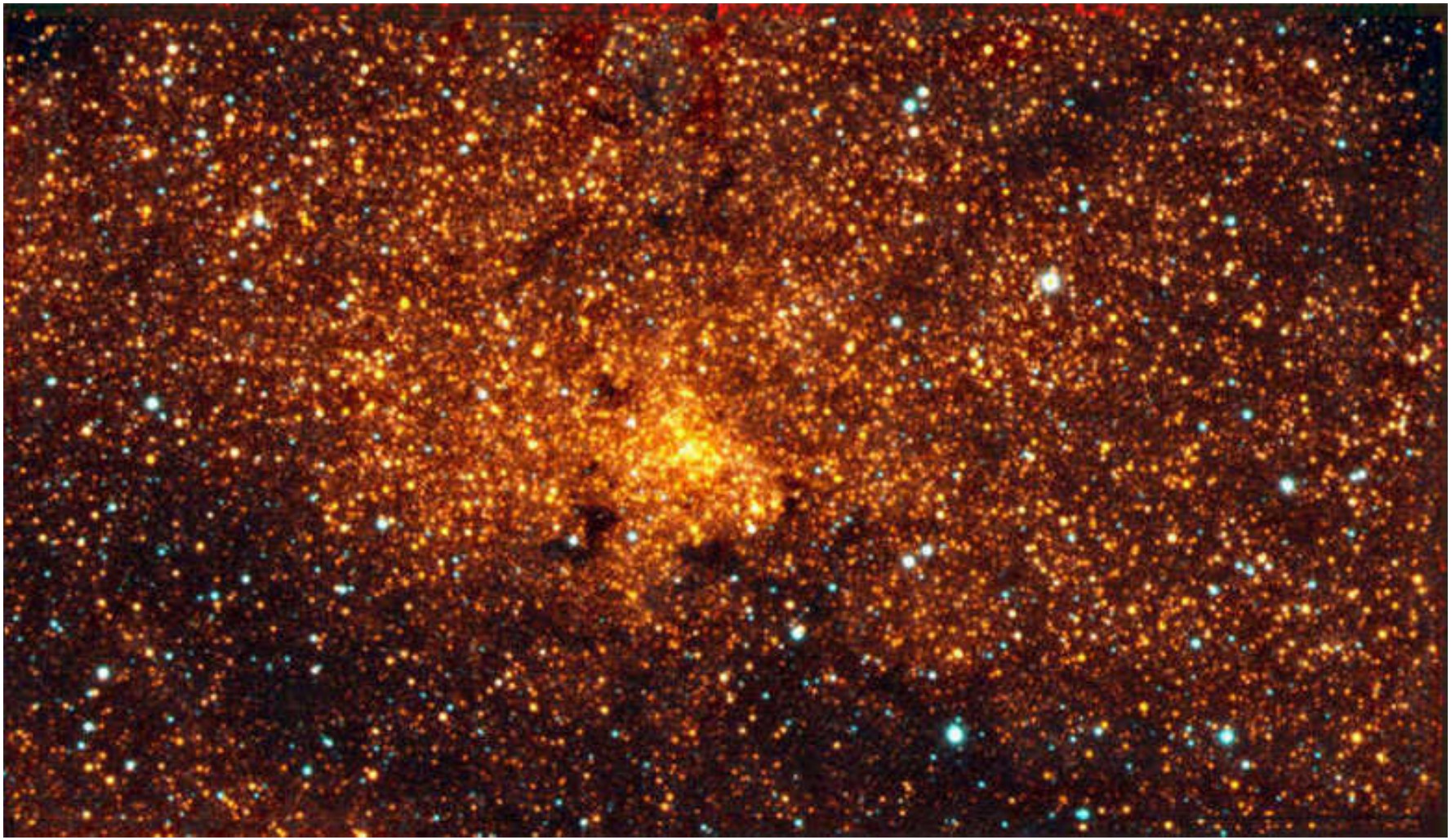


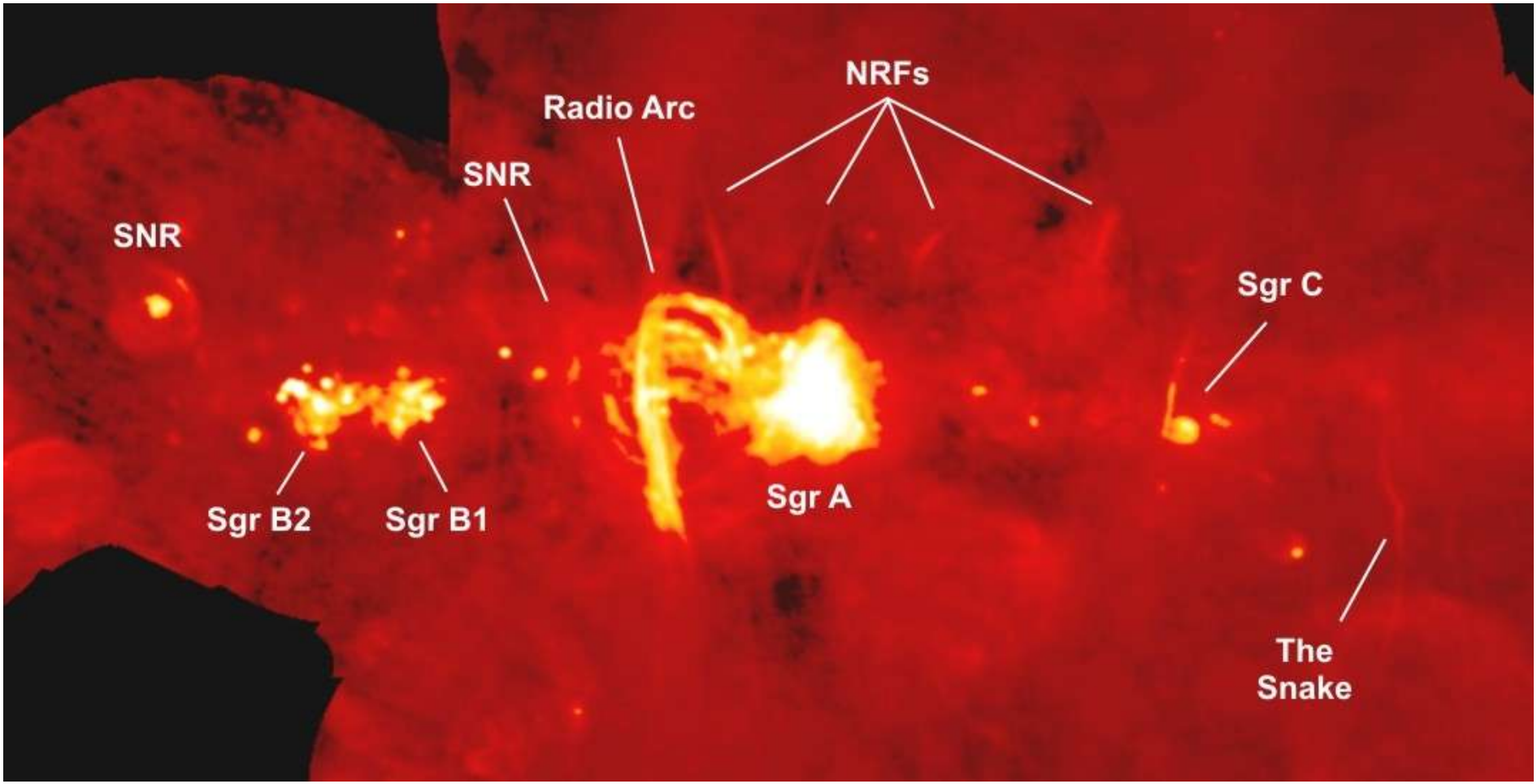
The Galactic centre (optical)



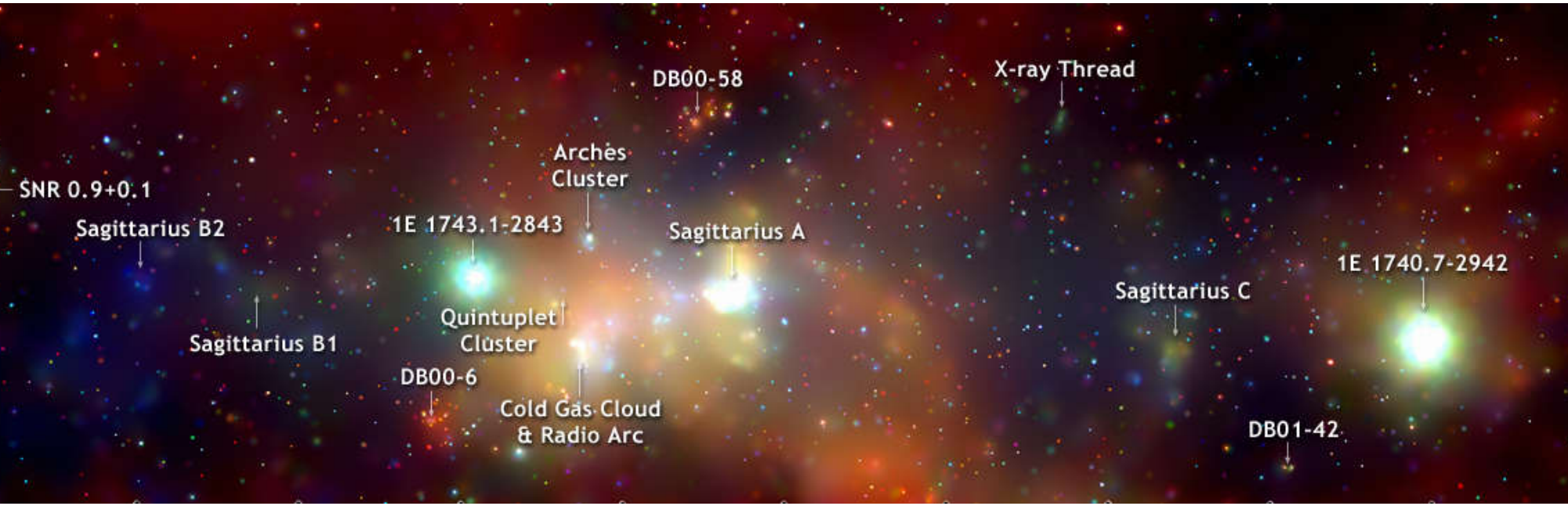
The Galactic centre (NIR)



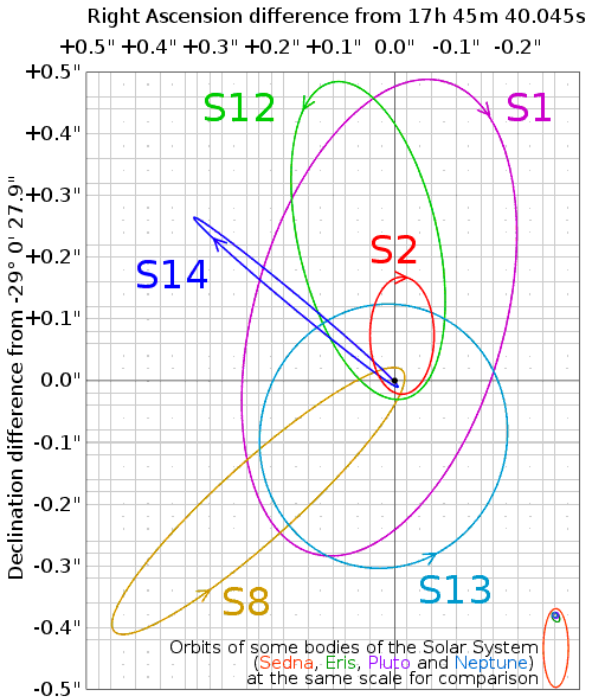
The Galactic centre (radio)



The Galactic centre (X rays)

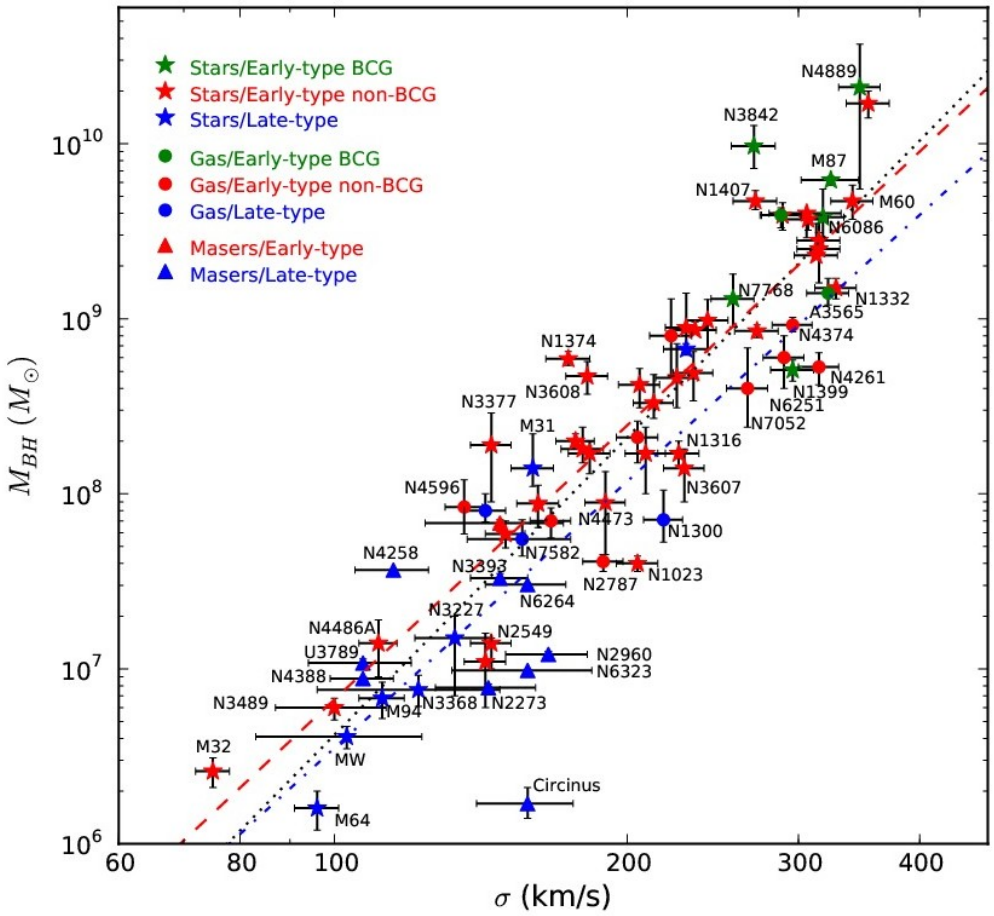


Supermassive black holes



Mass of Sagittarius A*

$\sim 10^6\ M_\odot$



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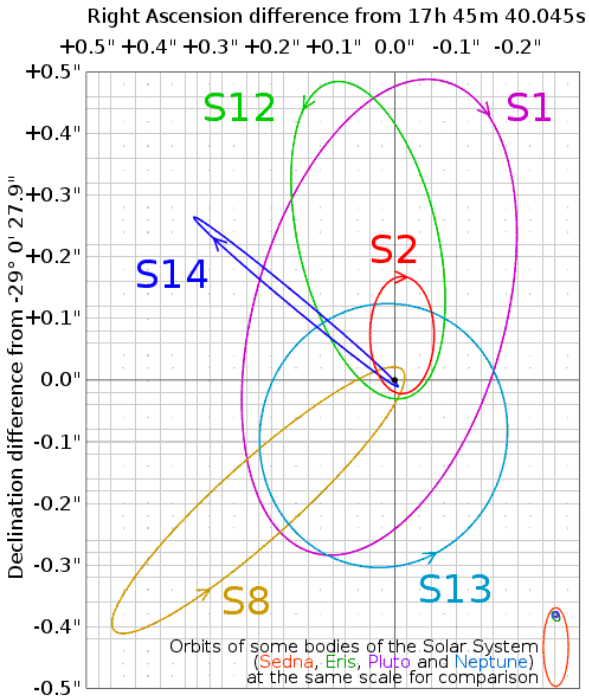

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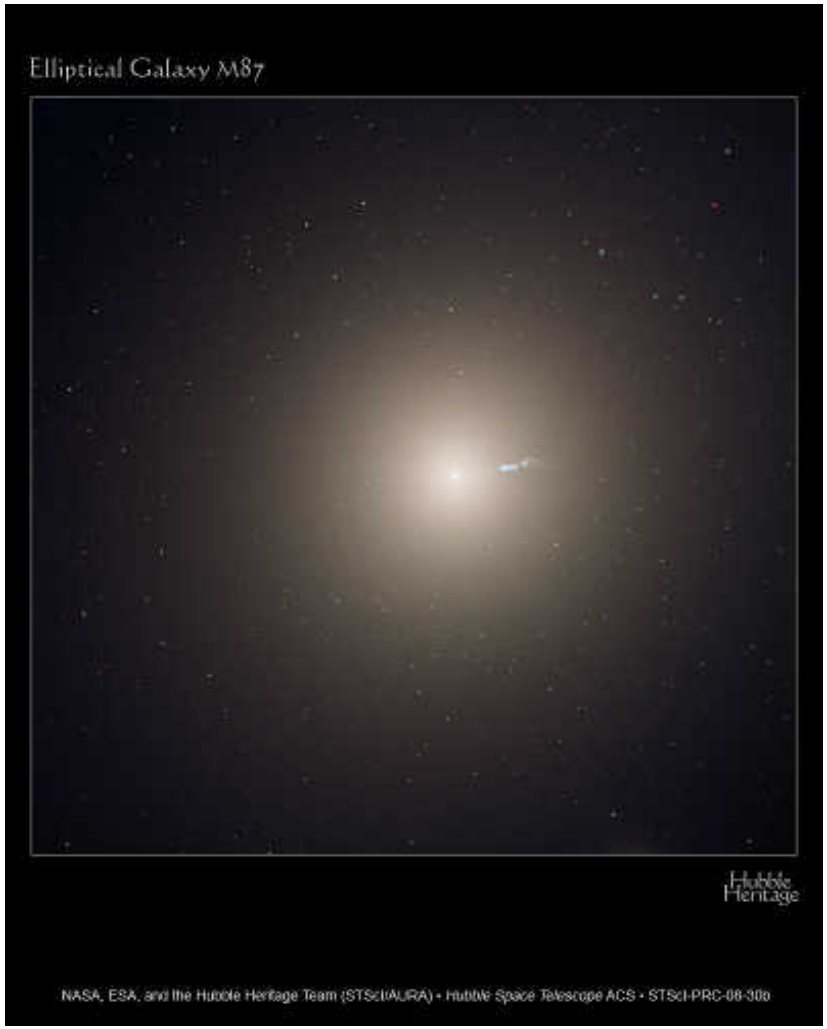
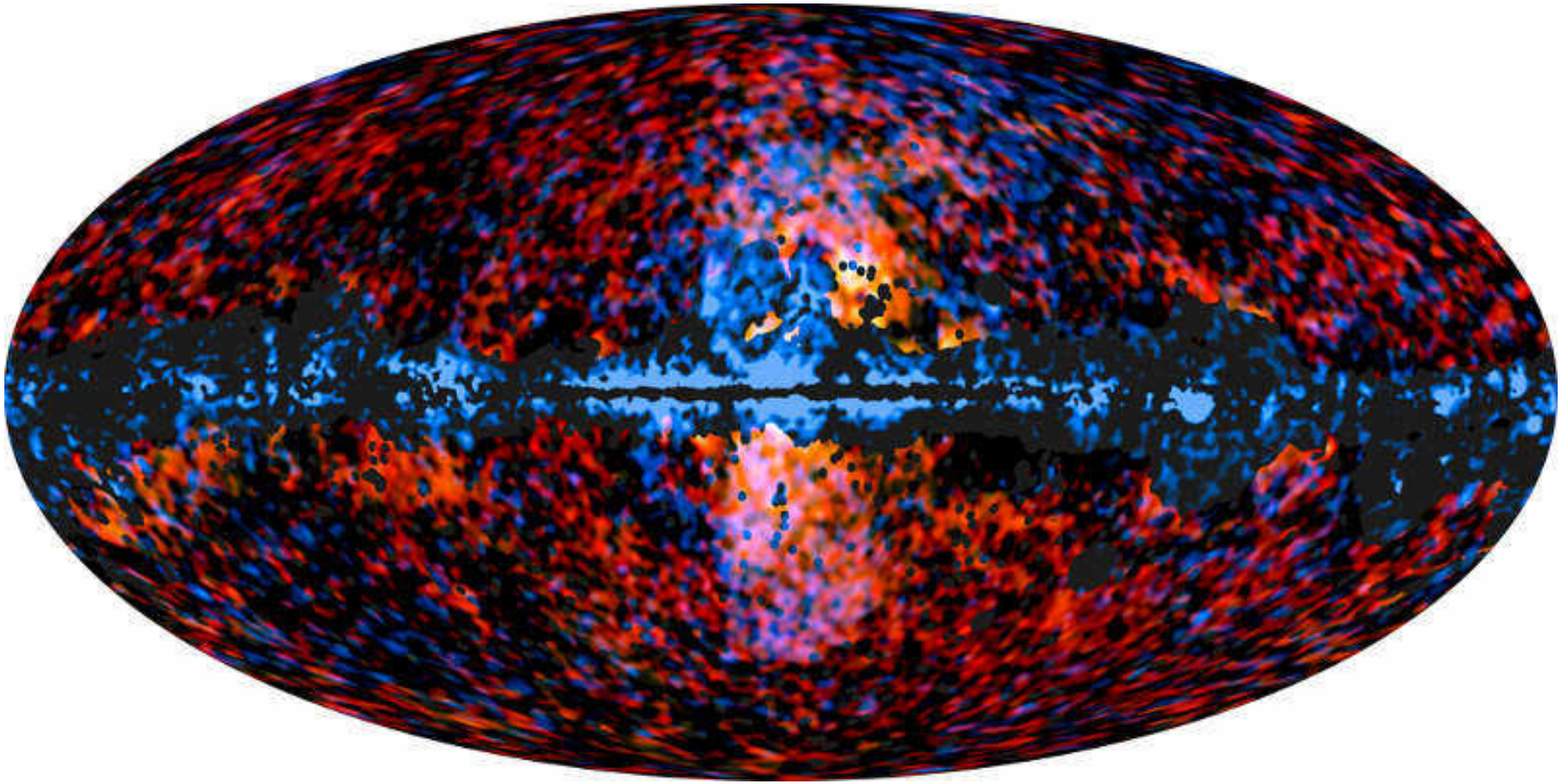
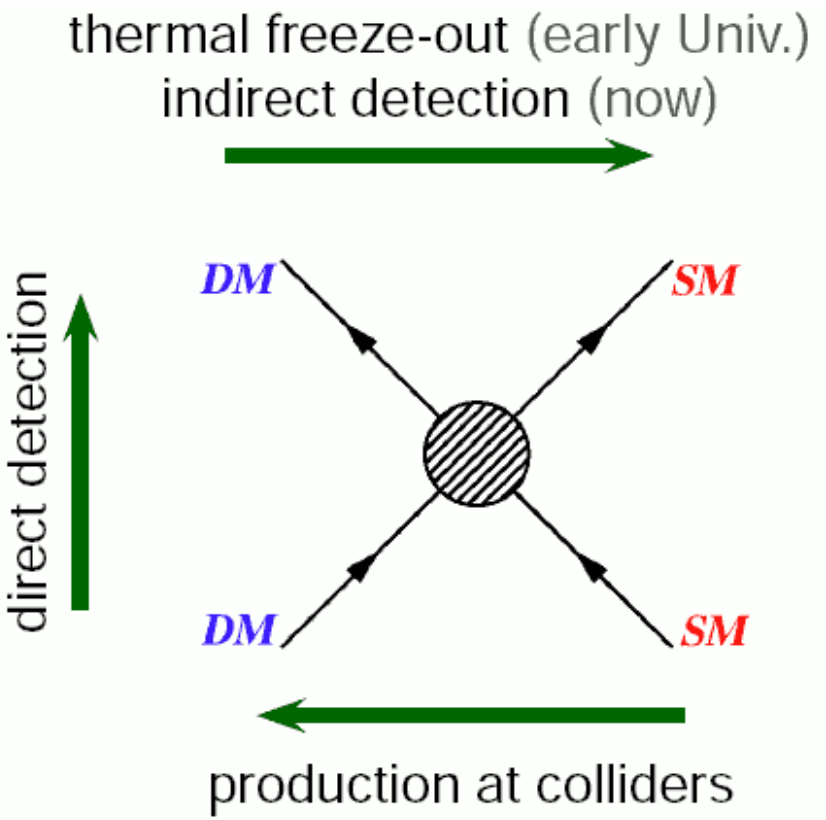


The Fermi bubbles



Not-so-dark matter (DM)



Injection rate

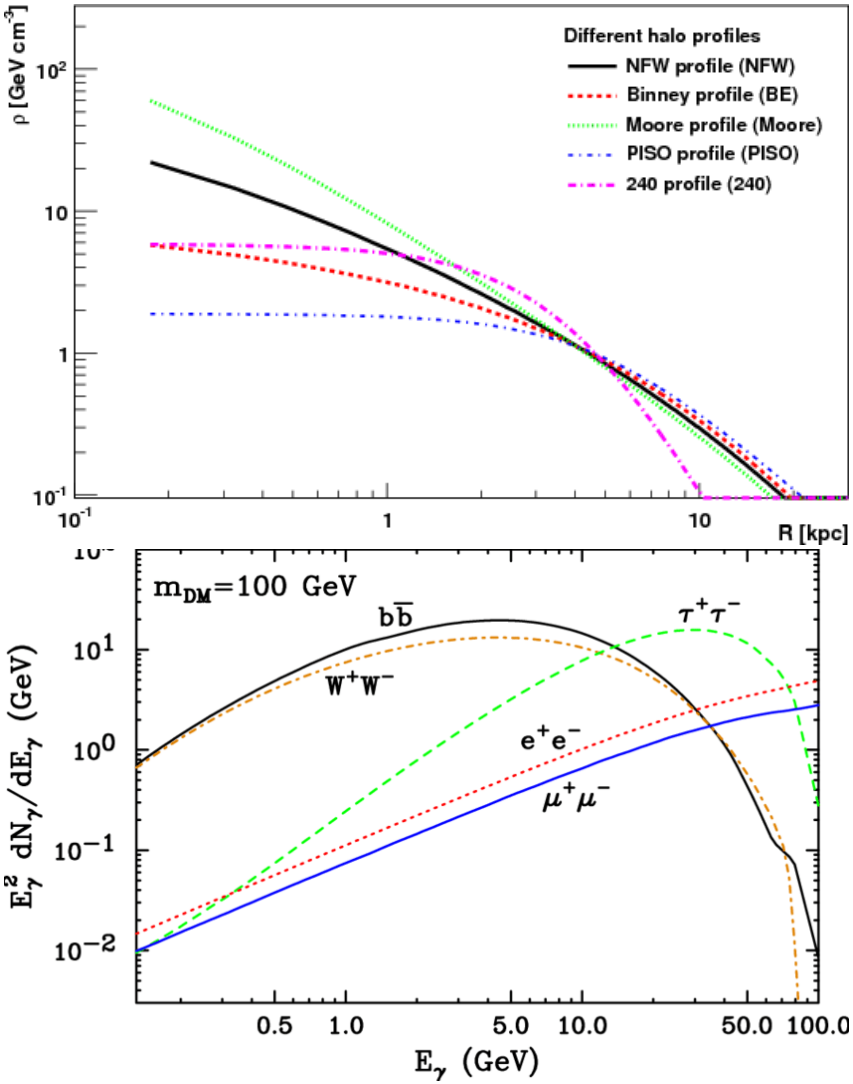
$$Q_{\rm ann} \sim \left(\frac{\rho_{\rm dm}}{m_{\rm dm}}\right)^2 \langle \sigma v \rangle \, \frac{{\rm d}N}{{\rm d}E}$$

$$\langle \sigma v \rangle_{\rm th} \sim 3 \times 10^{-26} \ {\rm cm}^3 \ {\rm s}^{-1}$$

$$\langle \sigma v \rangle_{\rm now} \sim a + b v^2$$

$$Q_{\rm decay} \sim \frac{\rho_{\rm dm}}{m_{\rm dm}} \, \Gamma \, \frac{{\rm d}N}{{\rm d}E}$$

Not-so-dark matter (DM)



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What could possibly go wrong?

Cosmic ray propagation

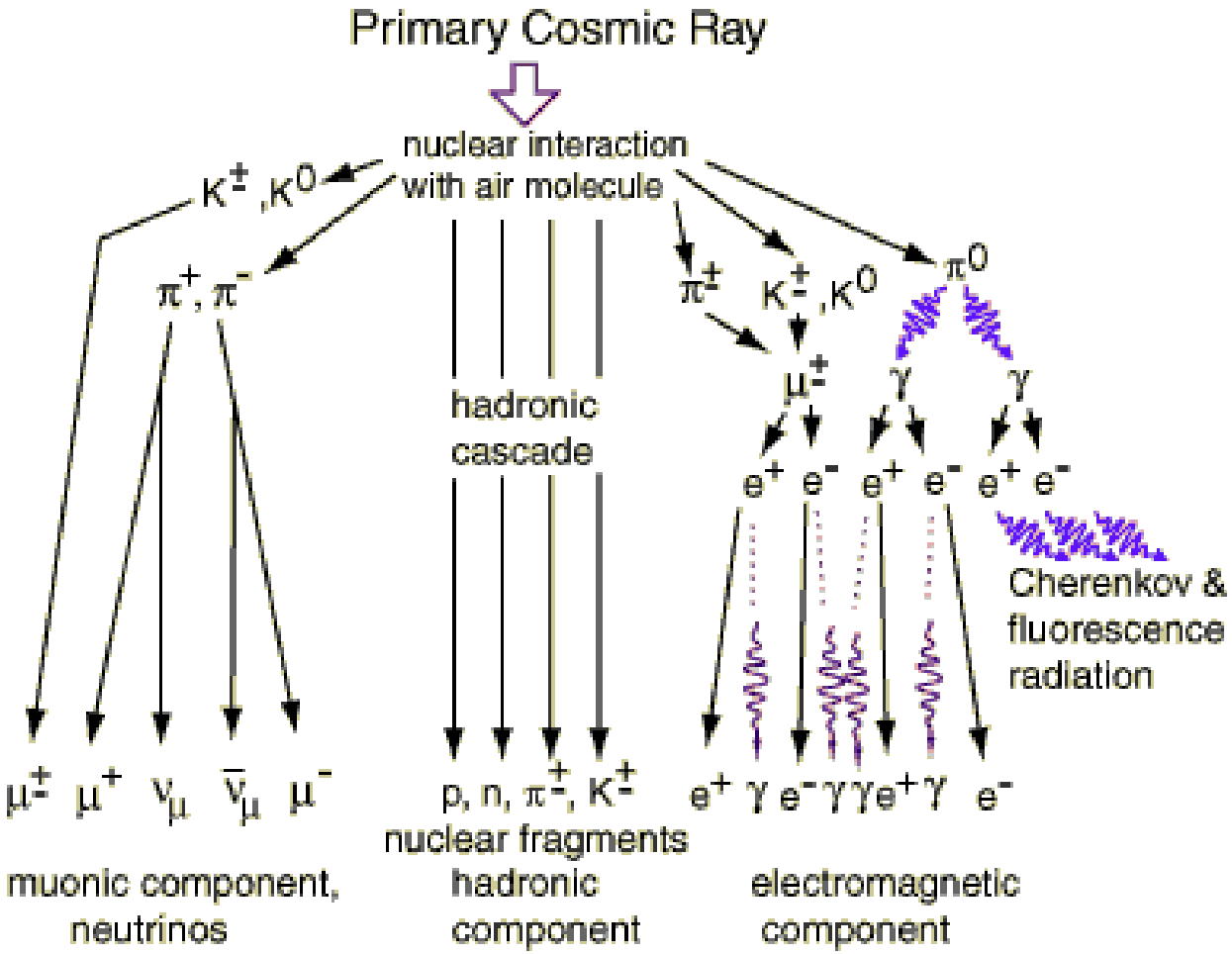
Diffusion-loss equation

cosmic ray energy spectrum

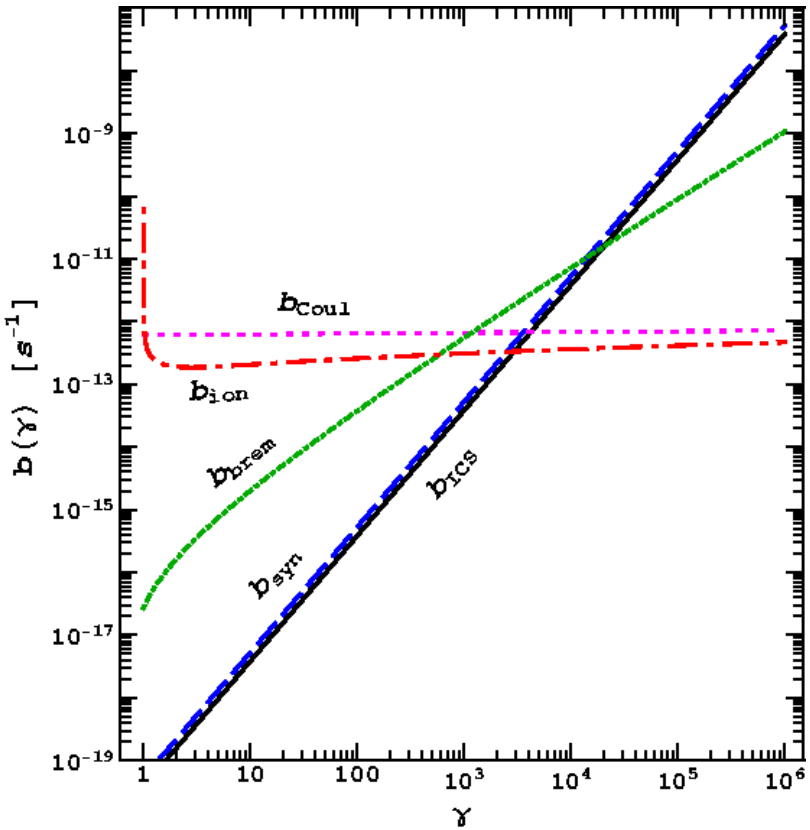
$$\frac{\partial}{\partial t}\frac{\mathrm{d}n}{\mathrm{d}\gamma}(\vec{x},\gamma) = \nabla\left[K(\vec{x},\gamma)\nabla\frac{\mathrm{d}n}{\mathrm{d}\gamma}(\vec{x},\gamma)\right] + \frac{\partial}{\partial\gamma}\left[b(\vec{x},\gamma)\frac{\mathrm{d}n}{\mathrm{d}\gamma}(\vec{x},\gamma)\right] + Q(\vec{x},\gamma)$$

steady-state | diffusion | energy losses | source term

Hadrons


Primary Cosmic Ray
nuclear interaction
with air molecule
$K^{\pm}, K^0$
π^+, π^-
hadronic
cascade
$\pi^{\pm}$
$K^{\pm}, K^0$
π^0
$\mu^{\pm}$
γ
γ
e^+ e^- e^+ e^- e^+ e^-
Cherenkov &
fluorescence
radiation
$\mu^{\pm}$ μ^+ ν_μ $\bar{\nu}_\mu$ μ^-
p, n, $\pi^{\pm}$, $K^{\pm}$
e^+ γ e^- γ γ e^+ γ e^-
muonic component,
neutrinos
nuclear fragments
hadronic
component
electromagnetic
component

Leptons



Inverse Compton Scattering (ICS)

$$b_{\mathrm{ICS}}(\gamma) = \frac{4}{3}\frac{\sigma_{\mathrm{T}}}{m_{\mathrm{e}}c}\gamma^2 U_{\mathrm{rad}}$$

Synchrotron

$$b_{\mathrm{syn}}(\gamma) = \frac{4}{3}\frac{\sigma_{\mathrm{T}}}{m_{\mathrm{e}}c}\gamma^2 U_{\mathrm{B}}$$

Bremsstrahlung

$$\frac{b_{\mathrm{brem}}(\gamma)}{1{,}51\times10^{-16}\ \mathrm{s}^{-1}} \approx n_{\mathrm{e}}\gamma\,[\ln(\gamma) + 0{,}36]$$

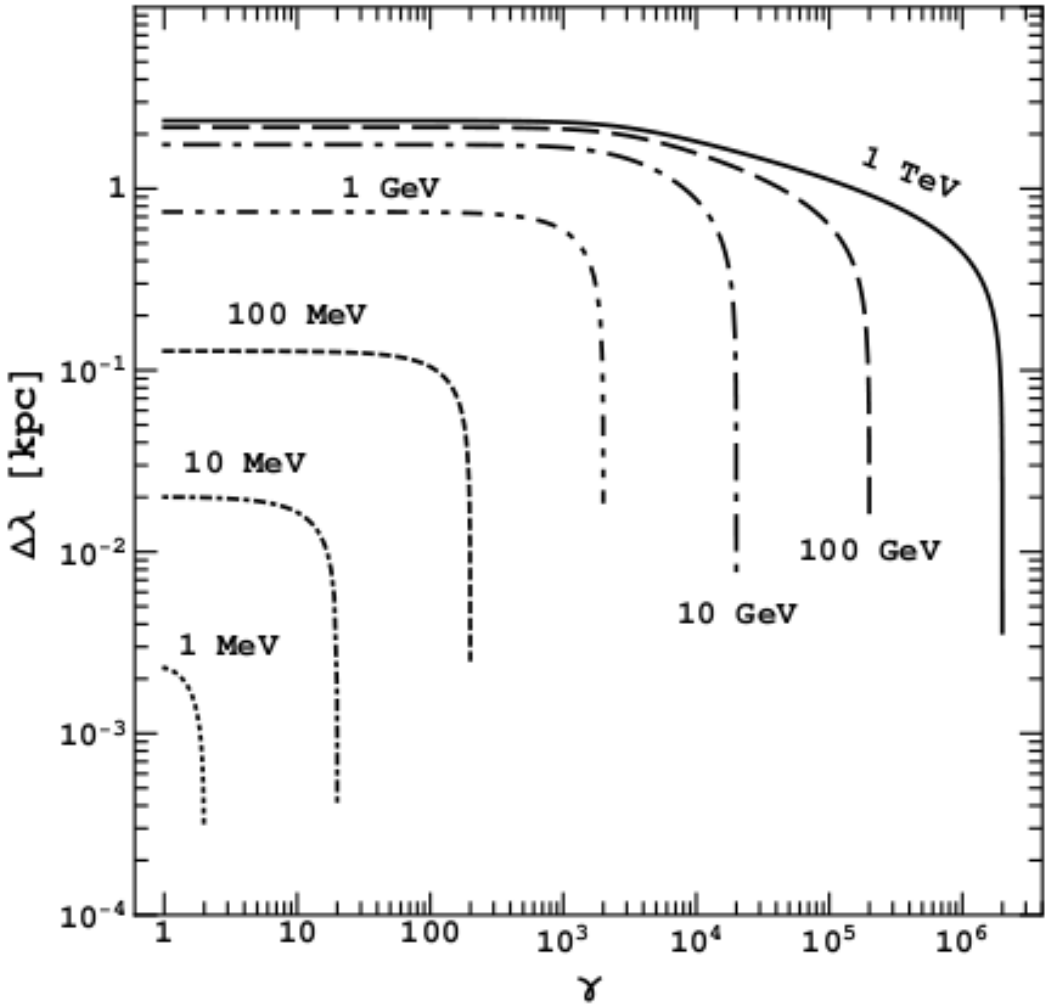
Ionisation

$$b_{\mathrm{ion}}(\gamma) = \frac{q_{\mathrm{e}}^4 n_{\mathrm{H}}}{8\pi\epsilon_0^2 m_{\mathrm{e}}^2 c^3 \sqrt{1-\frac{1}{\gamma^2}}} f(\gamma)$$

Coulomb collisions

$$\frac{b_{\mathrm{Coul}}(\gamma)}{1{,}2\times10^{-12}\ \mathrm{s}^{-1}} \approx n_{\mathrm{e}}\left[1 + \frac{\ln(\gamma/n_{\mathrm{e}})}{75}\right]$$

Diffusion


1 TeV
1 GeV
100 MeV
10 MeV
1 MeV
100 GeV
10 GeV
Δλ [kpc]
γ
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
1
10
100
10³
10⁴
10⁵
10⁶

Galactic structure

Interstellar medium (ISM)

- Density
- Temperature
- Ionisation

EM field

- Light (ISRF)
- Magnetic field

To be continued...