Introduction to astroparticle physics

Part 1: Andrii Neronov

Cosmic ray physics

... direct continuation of research started by V.Hess

Gamma-ray astronomy

.... application of particle physics methods in astronomy

Gravitational waves

Neutrino physics

* neutrino oscillations
* high-energy neutrino astronomy

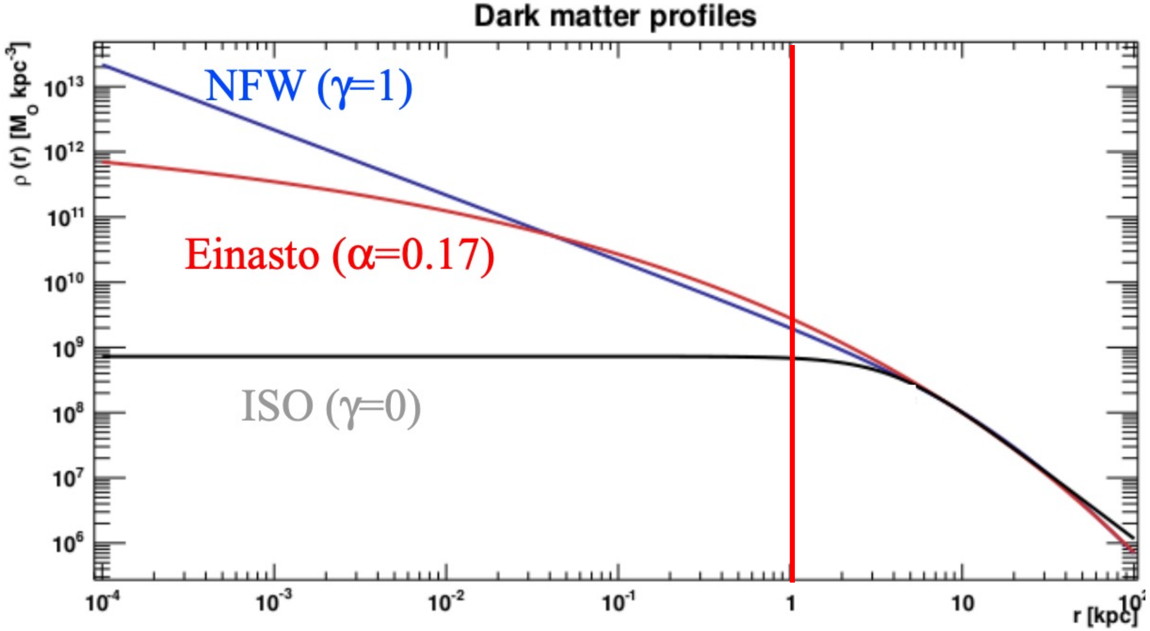
Dark matter physics

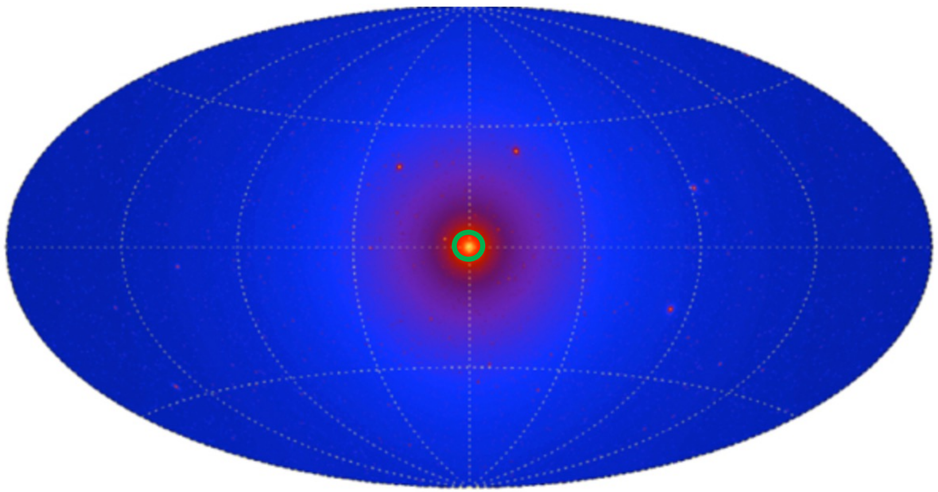
... direct continuation of research started by F.Zwicky

Particle physics in the Early Universe

... direct continuation of research started by Gamow

Dark matter signal as an astronomical source





The rate of interactions per unit volume is thus

$$\frac{n_{dm}}{t_{int}} = \sigma v n_{dm}^2 = \sigma v \left(\frac{\rho_{dm}}{m_{dm}}\right)^2$$

WIMP annihilation provides volume luminosity of the Milky Way

$$l(r) = 2m_{dm}\frac{n_{dm}}{t_{int}} \sim \frac{\sigma v \rho_{dm}^2(r)}{m_{dm}}$$

Total signal from e.g. the innermost 1 kpc of the Galaxy is

$$L \sim \frac{4\pi}{3} r^3 l \sim 10^{38}\left[\frac{100\text{ GeV}}{m_{dm}}\right]^{-1}\frac{\text{erg}}{\text{s}}$$

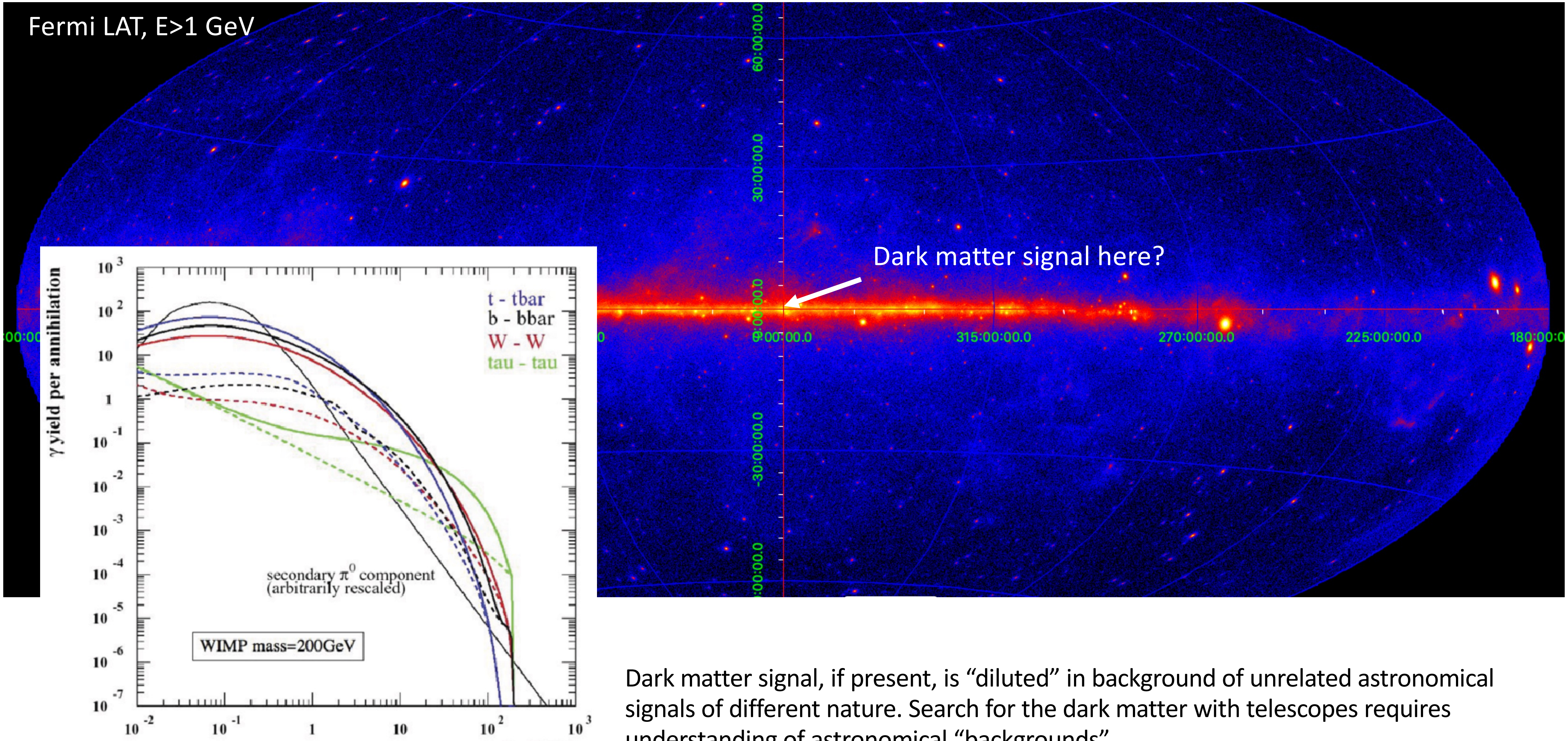
The Earth is at the distance $D \sim 8$ kpc from the center of the Galaxy, so that the kpc-scale innermost part of the dark matter halo spans an angle

$$\theta = \frac{r}{D} \simeq 7^\circ\left(\frac{r}{1\text{ kpc}}\right)$$

The flux of the source is

$$F = \frac{L}{4\pi D^2} \simeq 10^{-8}\left[\frac{100\text{ GeV}}{m_{dm}}\right]^{-1}\frac{\text{erg}}{\text{cm}^2\text{ s}}$$

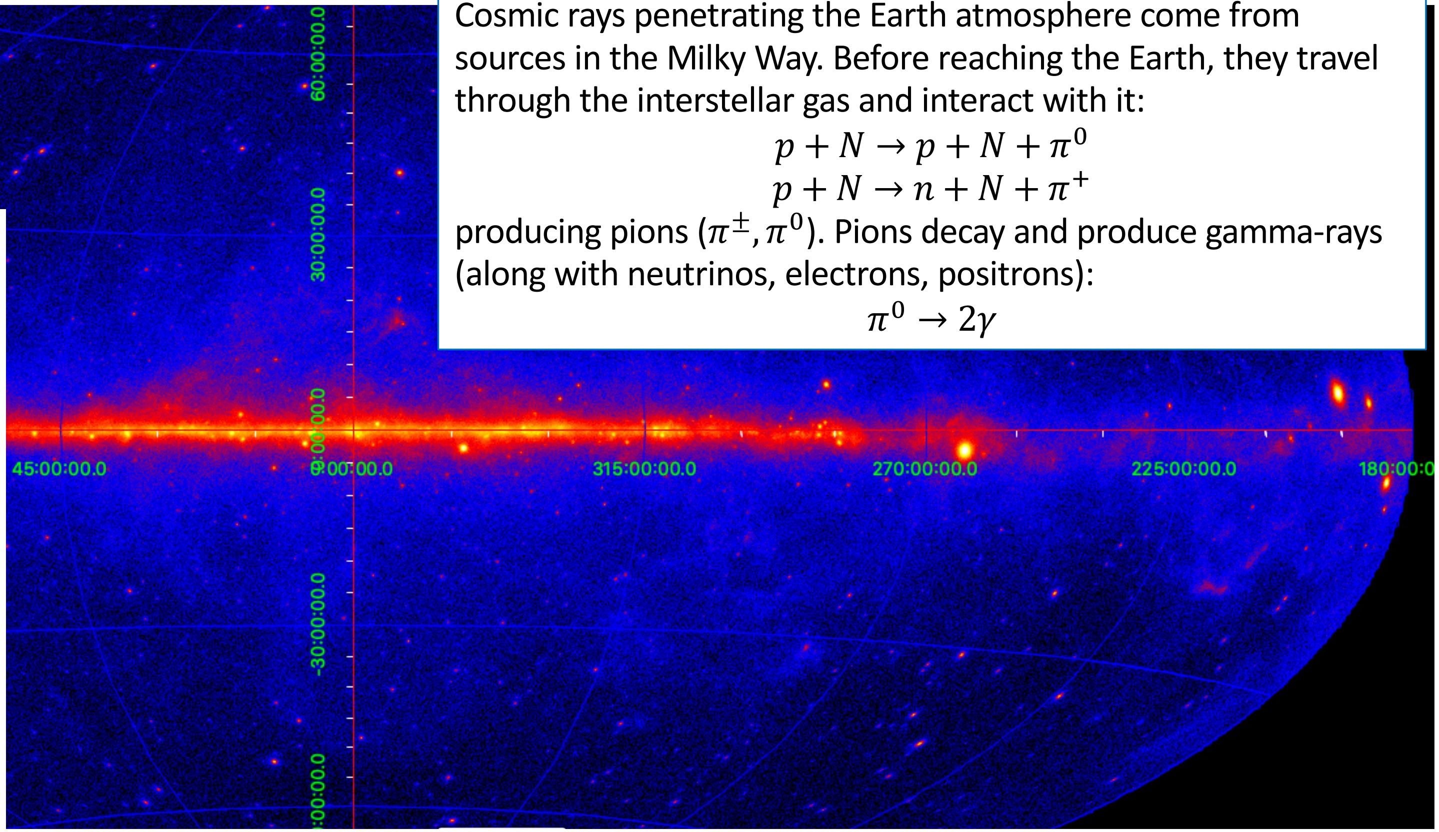
Dark matter signal vs. astronomical backgrounds

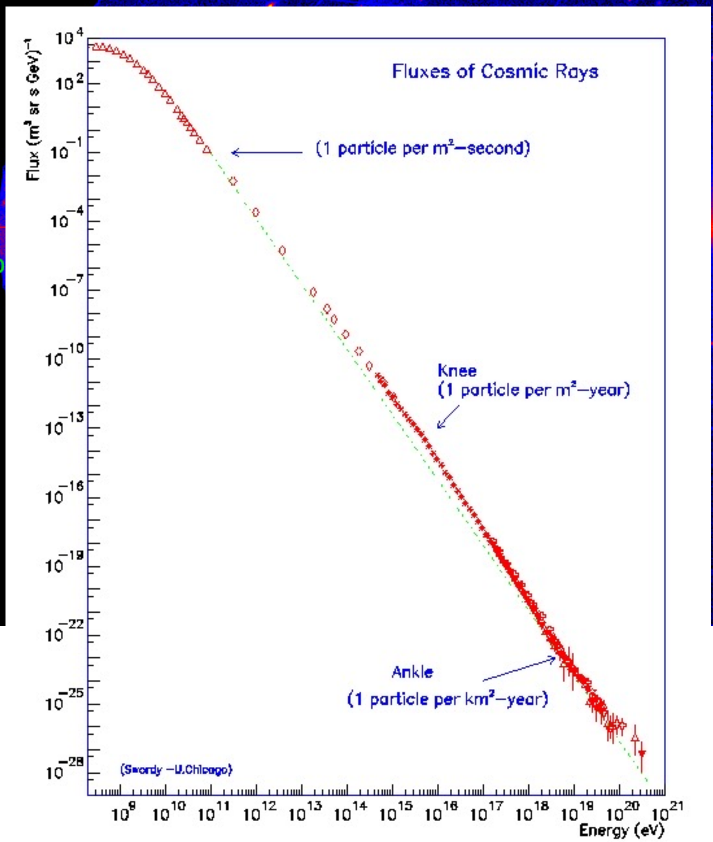


Model annihilation spectra

Dark matter signal, if present, is “diluted” in background of unrelated astronomical signals of different nature. Search for the dark matter with telescopes requires understanding of astronomical “backgrounds”.

Gamma-ray glow of the Milky Way





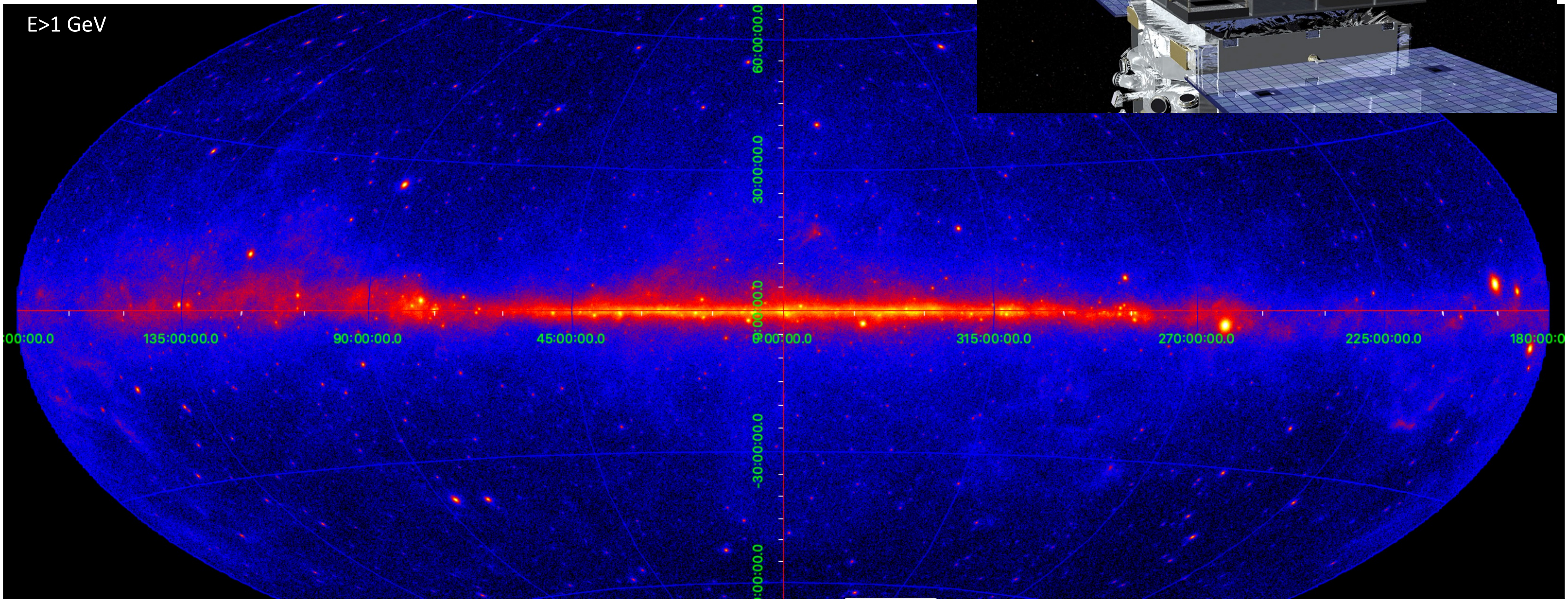
Cosmic rays penetrating the Earth atmosphere come from sources in the Milky Way. Before reaching the Earth, they travel through the interstellar gas and interact with it:

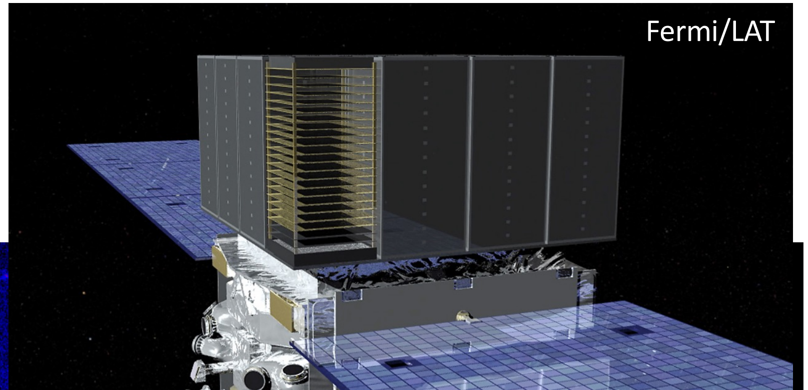
$$p + N \rightarrow p + N + \pi^0$$
$$p + N \rightarrow n + N + \pi^+$$

producing pions ($\pi^{\pm}, \pi^0$). Pions decay and produce gamma-rays (along with neutrinos, electrons, positrons):

$$\pi^0 \rightarrow 2\gamma$$

Gamma-ray and multi-messenger sources





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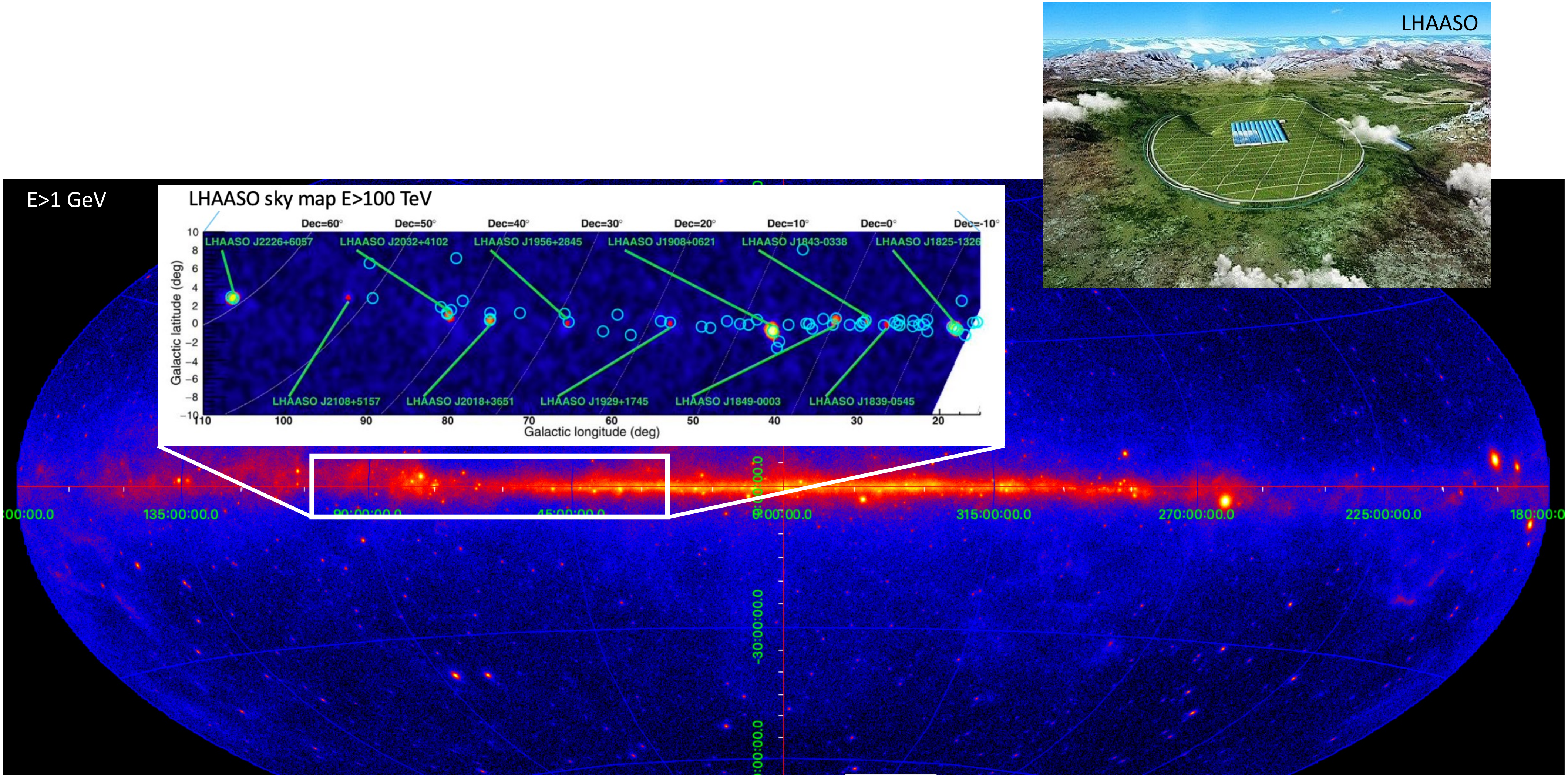

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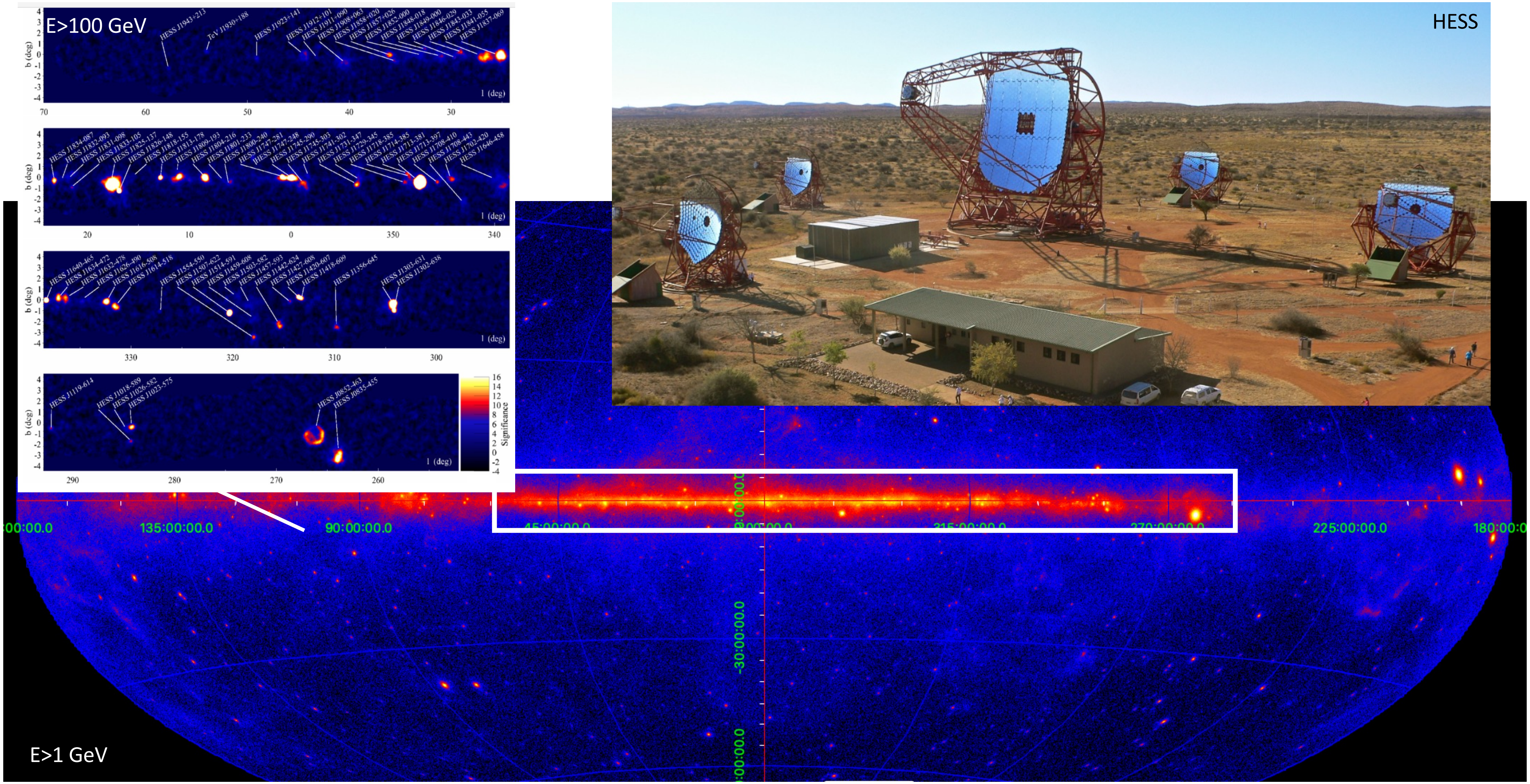

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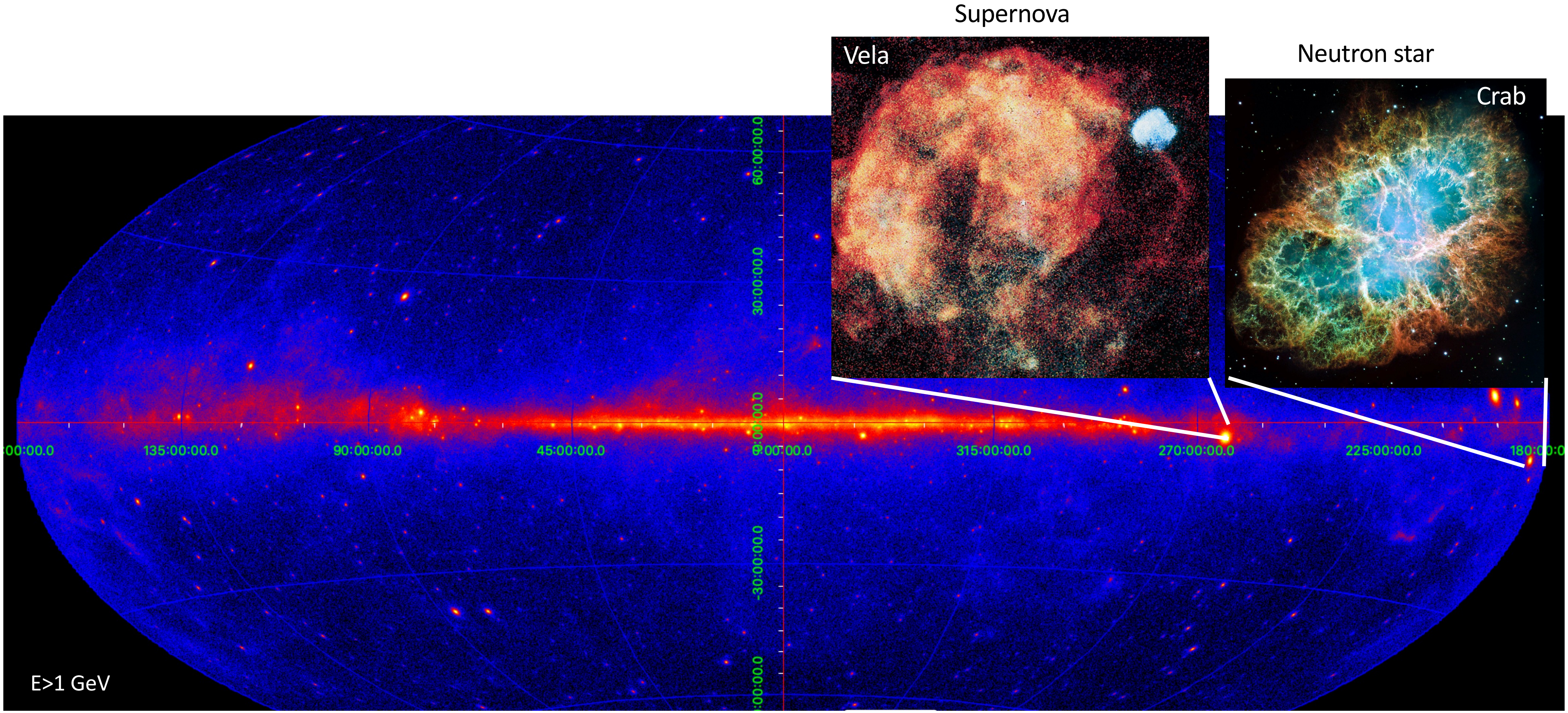
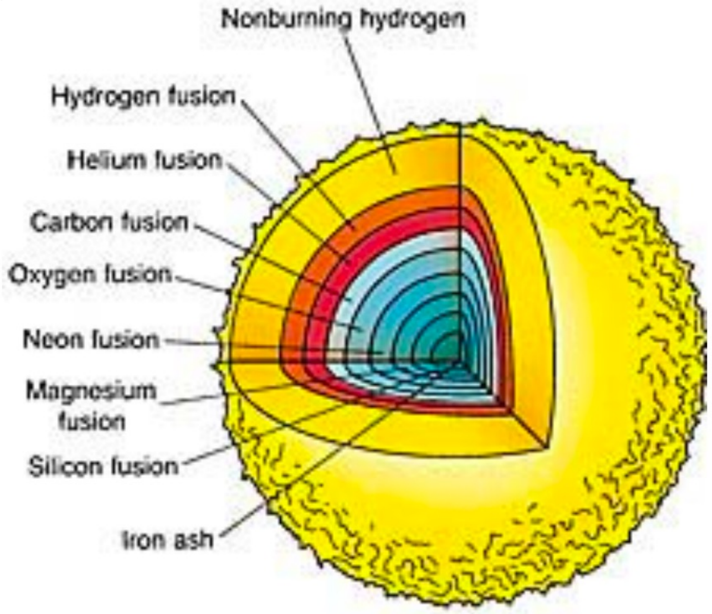


Evolution of massive stars

Stars with masses above $8M_\odot$ are able to synthesize nuclei up to iron (which has the largest binding energy). Iron is accumulated in the stellar core.



Stars are typically found in hydrostatic equilibrium: gravity force is counterbalanced by pressure gradient force:

$$\frac{dP}{dR} = \frac{G_N M \rho}{R^2}$$

The density of the iron core is high (up to $10^8\ \mathrm{g/cm^3}$).

The pressure is provided by the degenerate Fermi gas of electrons:

$$P = n_e v_e p_e$$

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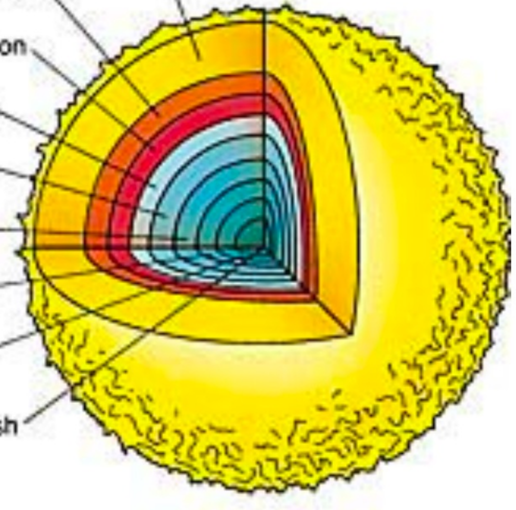

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$$\Delta x_\mathrm{e} \Delta p_e \sim 1$$

$$\Delta x_e \sim n_e^{-\frac{1}{3}} \sim \frac{m_e^{\frac{1}{3}}}{\rho_e^{\frac{1}{3}}};\ \ \Delta p_e \sim p_e = m_e v_e$$

$$m_e v_e \sim \frac{1}{\Delta x_e} \sim n_e^{\frac{1}{3}} = \left(Y_e n_p\right)^{\frac{1}{3}} = \left(\frac{Y_e \rho}{m_p}\right)^{\frac{1}{3}}$$

$$P \sim \frac{Y_e \rho}{m_p} \cdot \frac{1}{m_e} \left(\frac{Y_e \rho}{m_p}\right)^{\frac{1}{3}} \left(\frac{Y_e \rho}{m_p}\right)^{\frac{1}{3}} \sim \frac{Y_e^{\frac{5}{3}} \rho^{\frac{5}{3}}}{m_e m_p^{\frac{5}{3}}} \sim \frac{Y_e^{\frac{5}{3}} M^{\frac{5}{3}}}{m_e m_p^{\frac{5}{3}} R^5}$$

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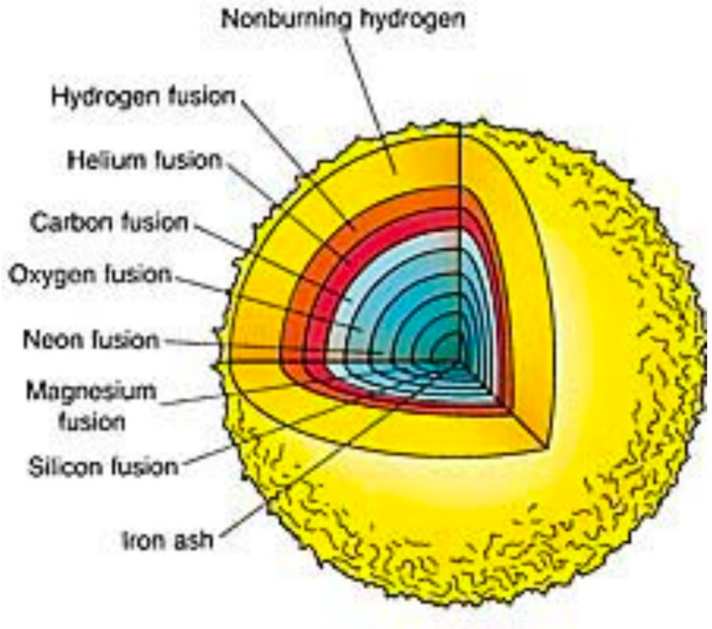

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The hydrostatic equilibrium equation:

$$\frac{Y_e^{\frac{5}{3}} M^{\frac{5}{3}}}{m_e m_p^{\frac{5}{3}} R^5} \cdot \frac{1}{R} \sim \frac{G_N M}{R^2}\frac{M}{R^3} = \frac{G_N M^2}{R^5}$$

$$\frac{Y_e^{\frac{5}{3}}}{m_e m_p^{\frac{5}{3}} G_N M^{\frac{1}{3}}} \sim R$$

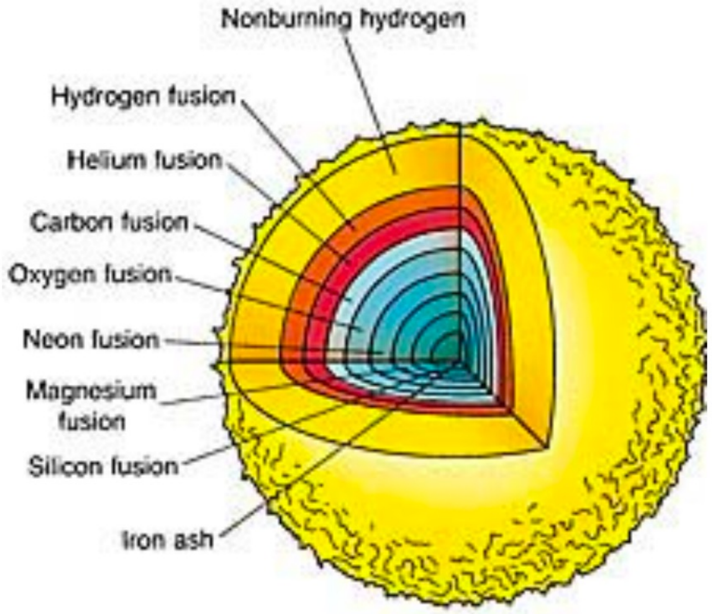
Mass-radius relation

Chandrasekhar mass

$$\frac{Y_e^{\frac{5}{3}}}{m_e m_p^{\frac{5}{3}} G_N M^{\frac{1}{3}}} \sim R$$

Iron accumulates in the core of the star and the mass of the core increases. This leads to the decrease of the radius and increase of the density

$$n_e = \frac{Y_e \rho}{m_p} \sim \frac{Y_e M}{m_p R^3} \sim \frac{Y_e M}{m_p} \cdot \frac{m_e^3 m_p^5 G_N^3 M}{Y_e^5} \sim \frac{m_e^3 m_p^4 G_N^3 M^2}{Y_e^4}$$



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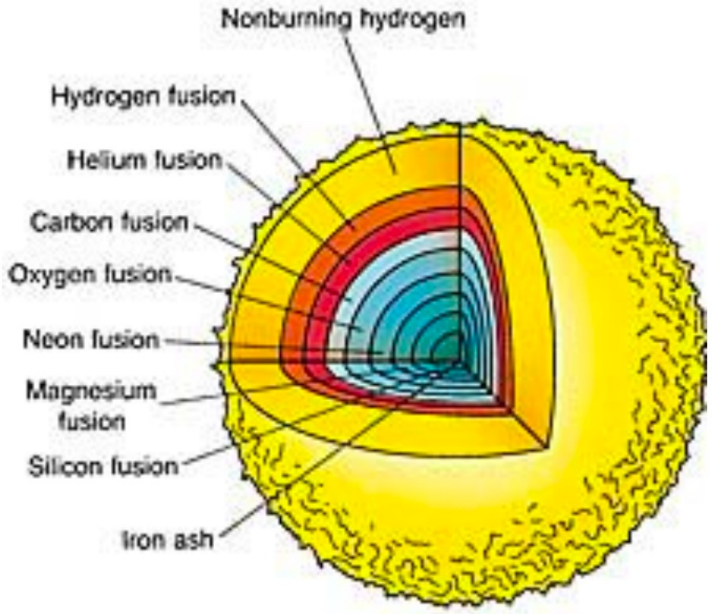

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Increase of the density leads to the increase of electron velocity:

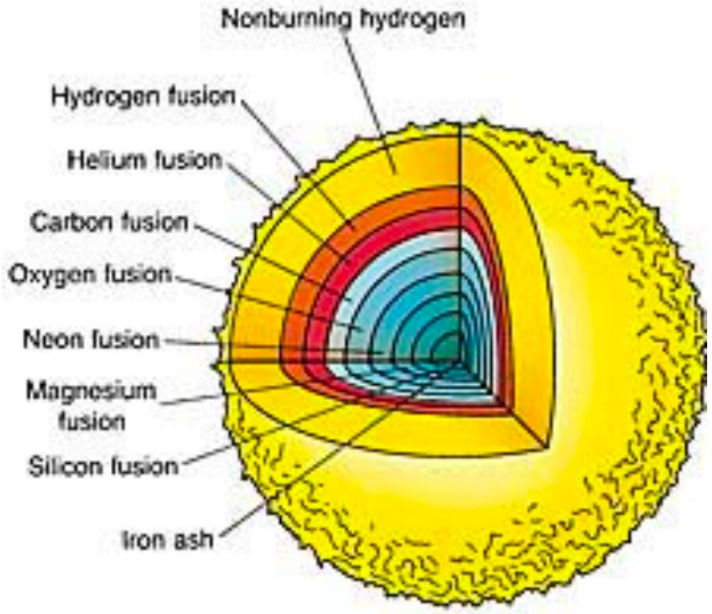
$$v_e \sim \frac{1}{m_e \Delta x_e} \sim \frac{n_e^{\frac{1}{3}}}{m_e} \sim \frac{1}{m_e} \cdot \frac{m_e m_p^{\frac{4}{3}} G_N M^{\frac{2}{3}}}{Y_e^{\frac{4}{3}}}$$

Electron velocity reaches the speed of light when

$$\frac{m_p^{\frac{4}{3}} G_N M^{\frac{2}{3}}}{Y_e^{\frac{4}{3}}} \sim 1; \qquad M \sim \frac{Y_e^2}{m_p^2 G_N^{\frac{3}{2}}} \simeq 1.4\ M_\odot$$

Chandrasekhar mass ($M_\odot \simeq 2\times 10^{33}$ g is the Solar mass)

Gravitational collapse



Hydrostatic equilibrium equation for relativistic degenerate electron gas:

$$\frac{dP}{dR} = \frac{G_N M\rho}{R^2}$$

$$P = n_e \mathbf{c} p_e$$

$$P \sim \frac{Y_e\rho}{m_p} \cdot \left(\frac{Y_e\rho}{m_p}\right)^{\frac{1}{3}} \sim \frac{Y_e^{\frac{4}{3}}\rho^{\frac{4}{3}}}{m_p^{\frac{4}{3}}} \sim \frac{Y_e^{\frac{4}{3}}M^{\frac{4}{3}}}{m_p^{\frac{4}{3}}R^4}$$

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$$\frac{Y_e^{\frac{4}{3}}M^{\frac{4}{3}}}{m_p^{\frac{4}{3}}R^4} \cdot \frac{1}{R} \sim \frac{G_N M^2}{R^5}$$

$$\frac{Y_e^{\frac{4}{3}}}{m_p^{\frac{4}{3}}G_N} \sim M^{\frac{2}{3}}$$

Hydrostatic equilibrium supported by relativistic electron gas is possible only for a fixed mass $M = M_{Ch}$. As soon as the mass of the iron core exceeds the Chandrasekhar limit, the core collapses under the force of gravity.

Gravitational collapse

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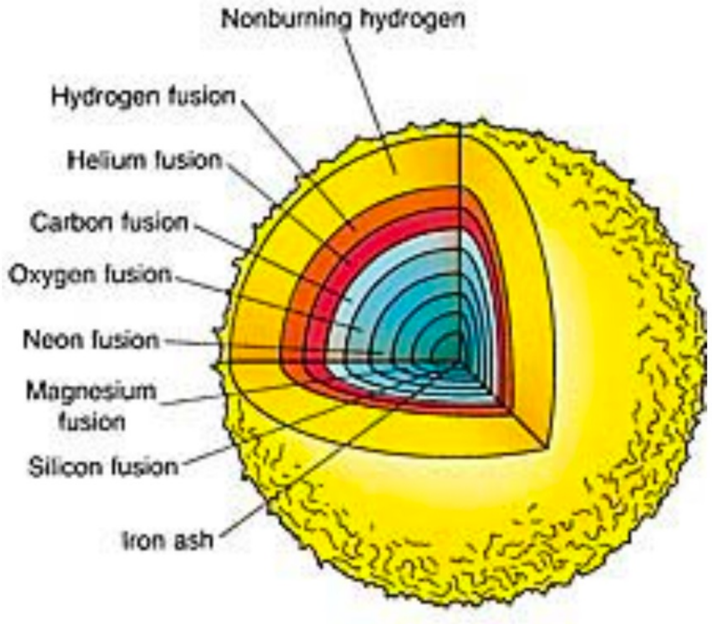
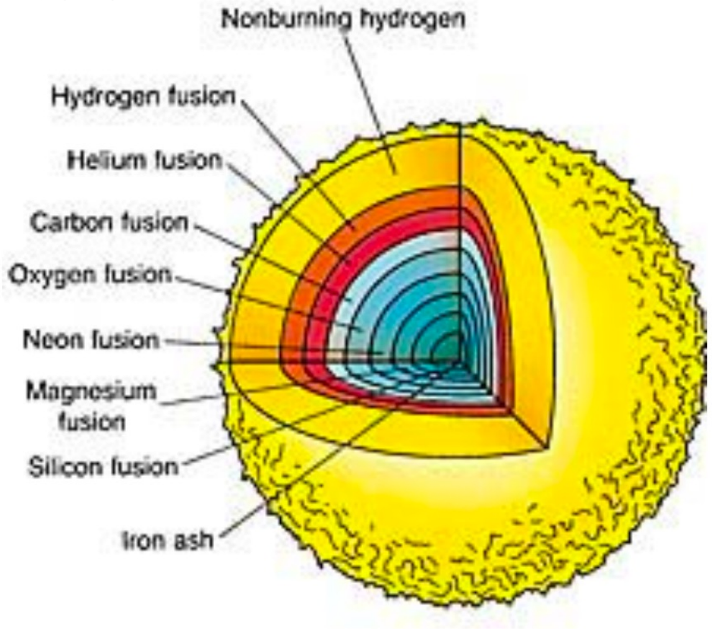


$$M_{Ch} = \frac{Y_e^2}{m_p^2 G_N^{\frac{3}{2}}}$$

$$R_{Ch} \sim \frac{Y_e^{\frac{5}{3}}}{m_e m_p^{\frac{5}{3}} G_N M_{Ch}^{\frac{1}{3}}} \simeq 3\times 10^8 \text{ cm}$$

$$\rho_{Ch} \sim \frac{M_{Ch}}{R_{Ch}^3} \simeq 10^8 \frac{\text{g}}{\text{cm}^3}$$

Gravitational collapse of stellar core



In the absence of counterbalancing pressure the collapse proceeds on the free-fall time scale:

$$v \sim \sqrt{\frac{G_N M_{Ch}}{R_{Ch}}} < 1\ s$$

The density rapidly grows until it reaches the nuclear density scale:

$$\rho_{nuc} \sim \frac{m_p}{(10^{-13}\ \mathrm{cm})^3} \sim 10^{15}\ \frac{\mathrm{g}}{\mathrm{cm}^3}$$

This happens when the size of the collapsed core is down to

$$R \sim \left(\frac{M_{Ch}}{\rho_{nuc}}\right)^{\frac{1}{3}} \sim \left(\frac{10^{33}\ \mathrm{g}}{10^{15}\ \frac{\mathrm{g}}{\mathrm{cm}^3}}\right)^{\frac{1}{3}} \sim 10^6 \mathrm{cm}$$

Neutronization

$$\rho \sim 10^{15} \frac{\text{g}}{\text{cm}^3}$$

$$R \sim \left(\frac{M}{\rho}\right)^{\frac{1}{3}} \sim 10^6 \text{ m}$$

Increasing density induces destruction of atomic nuclei, the matter becomes degenerate gas of nucleons: protons and neutrons. Protons can be converted to neutrons via inverse beta decay:

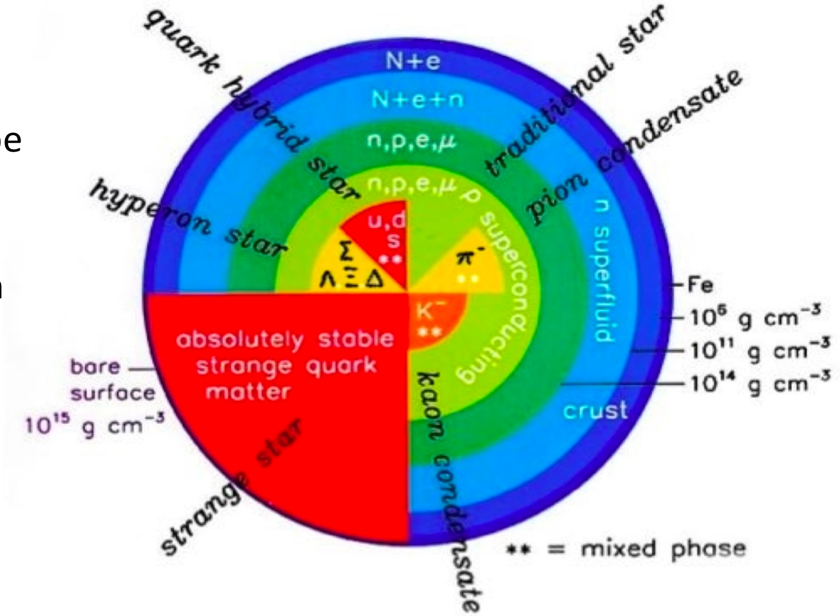
$$p + e^- \rightarrow n + \nu_e$$

Free neutrons do not decay, because their decay would release an electron into highly degenerate electron gas:

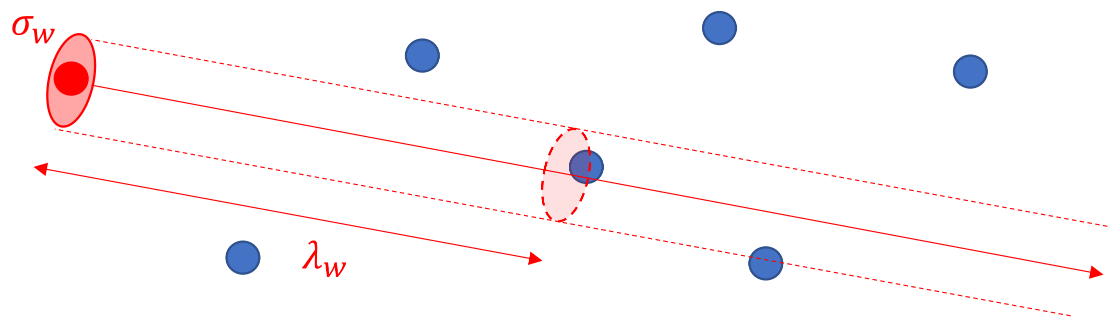
$$n \rightarrow p + e^- + \bar{\nu}_e$$

Fermi velocity in this gas is close to the speed of light, Fermi energy is relativistic. All energy levels to which the released electron might be deposited are already occupied.

As a result, large part of protons is converted into neutrons. A “neutron star” is formed.



Neutrino emission



$$t_w < t_H \ldots\ldots \rightarrow \lambda_w < R$$

Particles (neutrinos, photons) can escape from the neutron star if their mean free path is longer than the size of the star:

$$\lambda_\nu = \frac{1}{\sigma_w n_n} > R$$

$$\sigma_W \sim G_F^2 E^2 \simeq (10^{-5}\ \mathrm{GeV}^{-2})^2 (100\ \mathrm{MeV})^2 \sim 10^{-39}\ \mathrm{cm}^2$$

This is not the case for the neutron stars: neutrinos are trapped inside. Before escaping, they perform a random walk, so that their escape time is

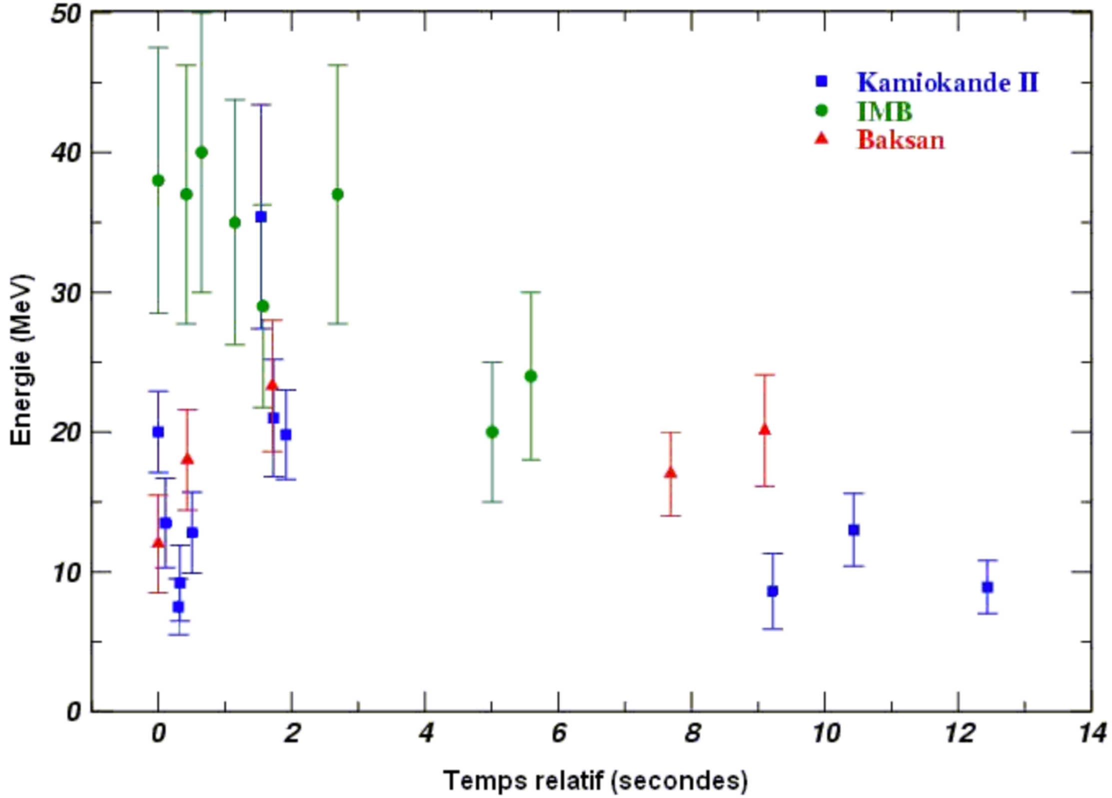
$$t_{esc} \sim \frac{R^2}{\lambda_\nu}$$

Neutrinos finally escape from a surface layer at which $\lambda_w \geq R$ ("neutrinosphere", by analogy with the "photosphere" of stars).

N.B.: photon escape time is much longer than that of neutrinos, because for photons $\sigma = \sigma_T \sim 10^{-24}\ \mathrm{cm}^2 \gg \sigma_W$.

Neutrinos from SN 1987A

Visible light image of SN 1987A supernova in Large Magellanic cloud 30 years after the explosion.



Neutrino signal.

Rate of supernovae in our Galaxy is “several” per century. Since neutrino detection experiments are operating, only one supernova has exploded at a relatively small distance, in Large Magellanic Cloud at 50 kpc.