Non-thermal radiative processes

Yago Ascasibar (Módulo 15, despacho 506)

Procesos Radiativos en Astrofísica
Máster en Física Teórica (Astrofísica)

Local Thermodynamic Equilibrium (LTE)

Radiative transport

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = j_\nu - \alpha I_\nu$$

$$\tau = \int \alpha \, \mathrm{d}s$$

Kirchoff Law (LTE)

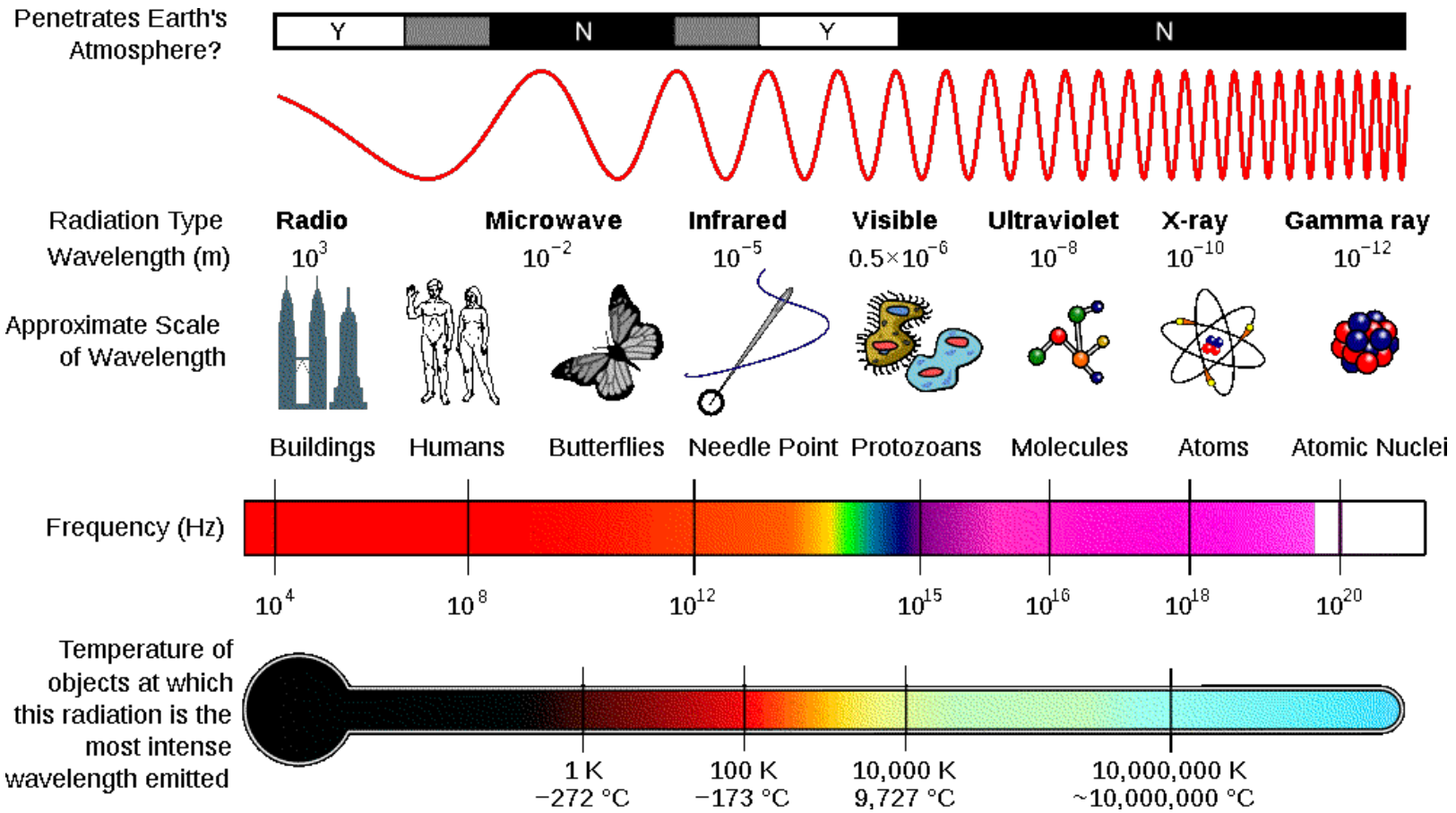
$$j_\nu = \alpha \, B_\nu(T)$$

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}\tau} = B_\nu(T) - I_\nu$$

Radiative transport at constant temperature

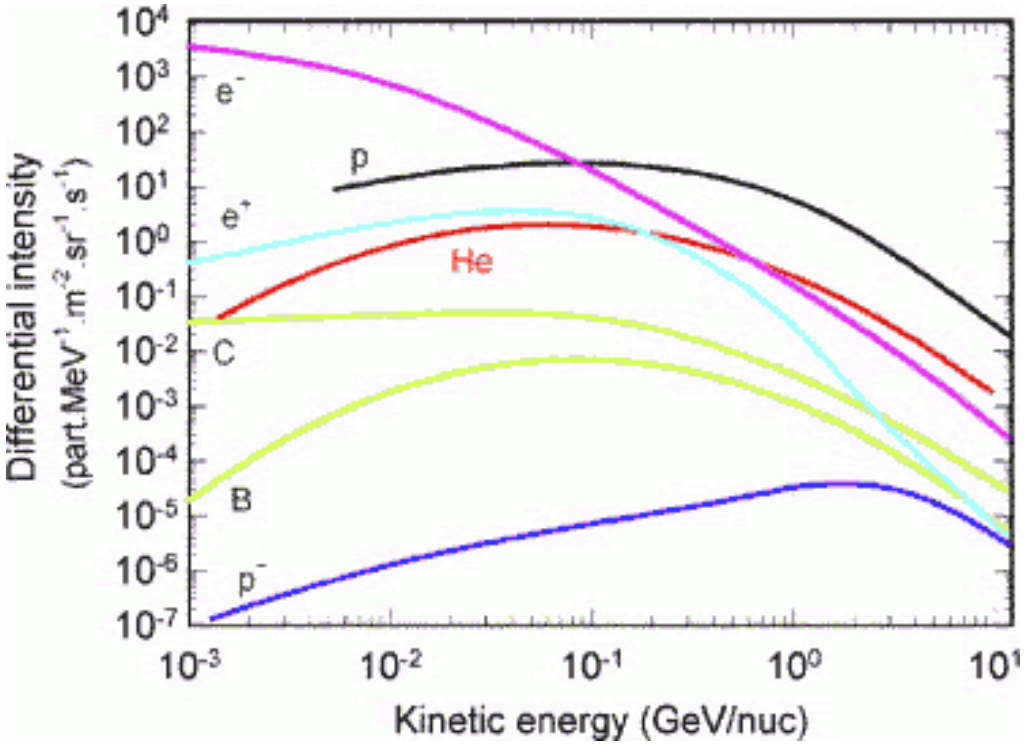
$$I_\nu(\tau) = I_\nu(\tau = 0)e^{-\tau} + B_\nu(T)(1 - e^{-\tau})$$

Local Thermodynamic Equilibrium (LTE)



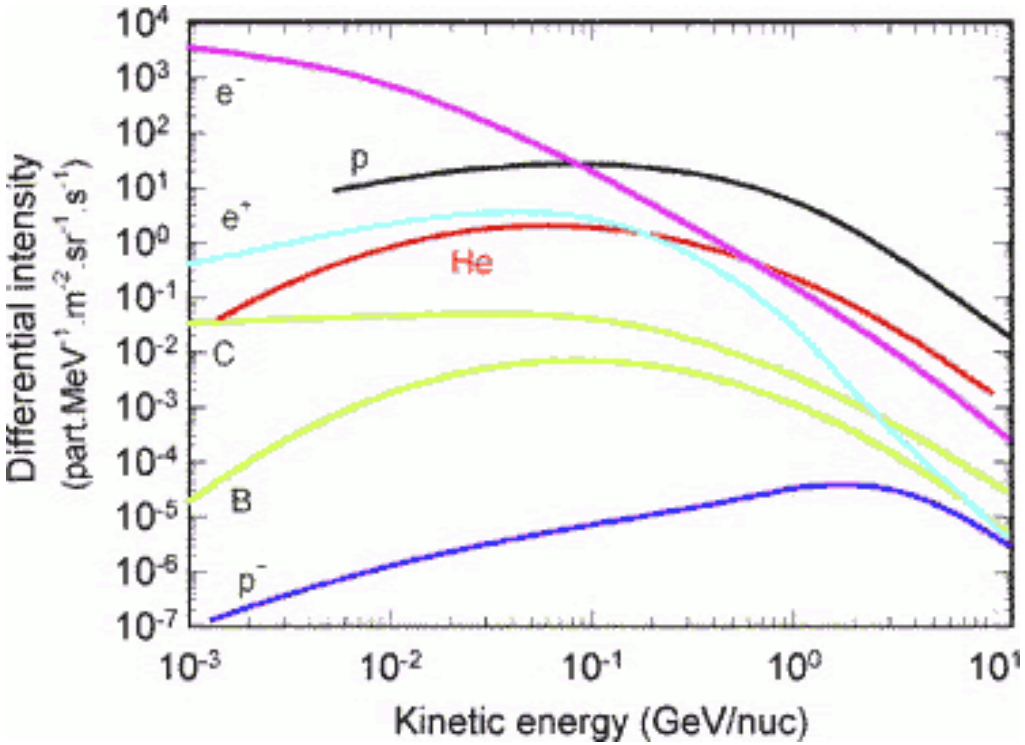
$$1\ \mathrm{eV} \sim h \times 10^{5}\ \mathrm{GHz} \sim \frac{hc}{10^{4}\ \text{Å}} \sim \frac{hc}{1\ \mu m} \sim k \times 10^{4}\ \mathrm{K} \sim 0{,}6 m_p (10\ \mathrm{km/s})^2$$

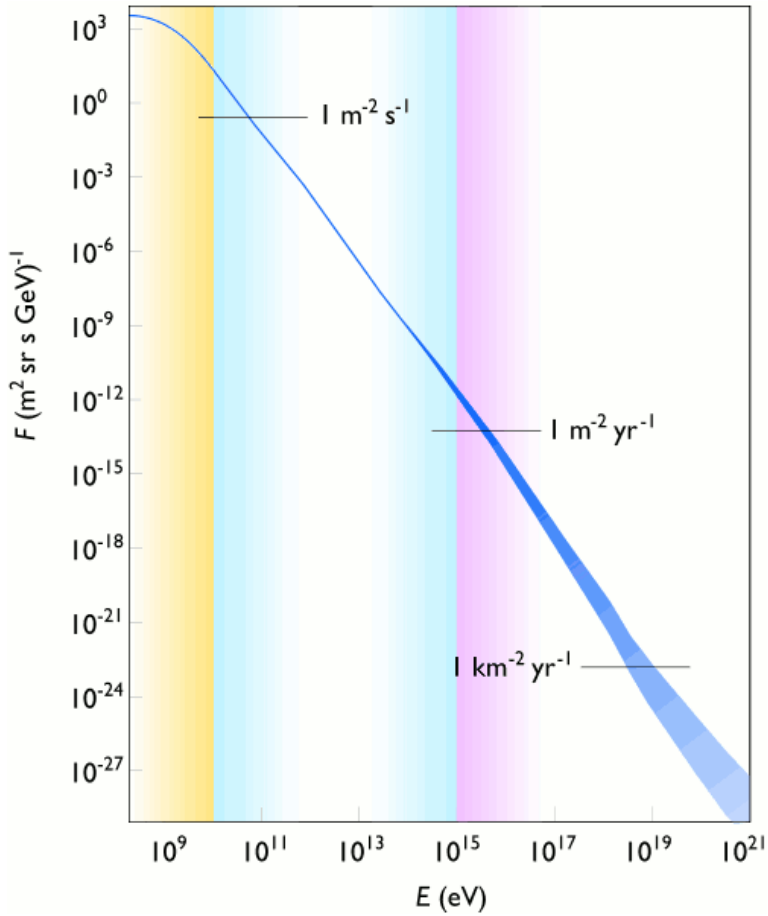
Cosmic rays



- 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}

Outline

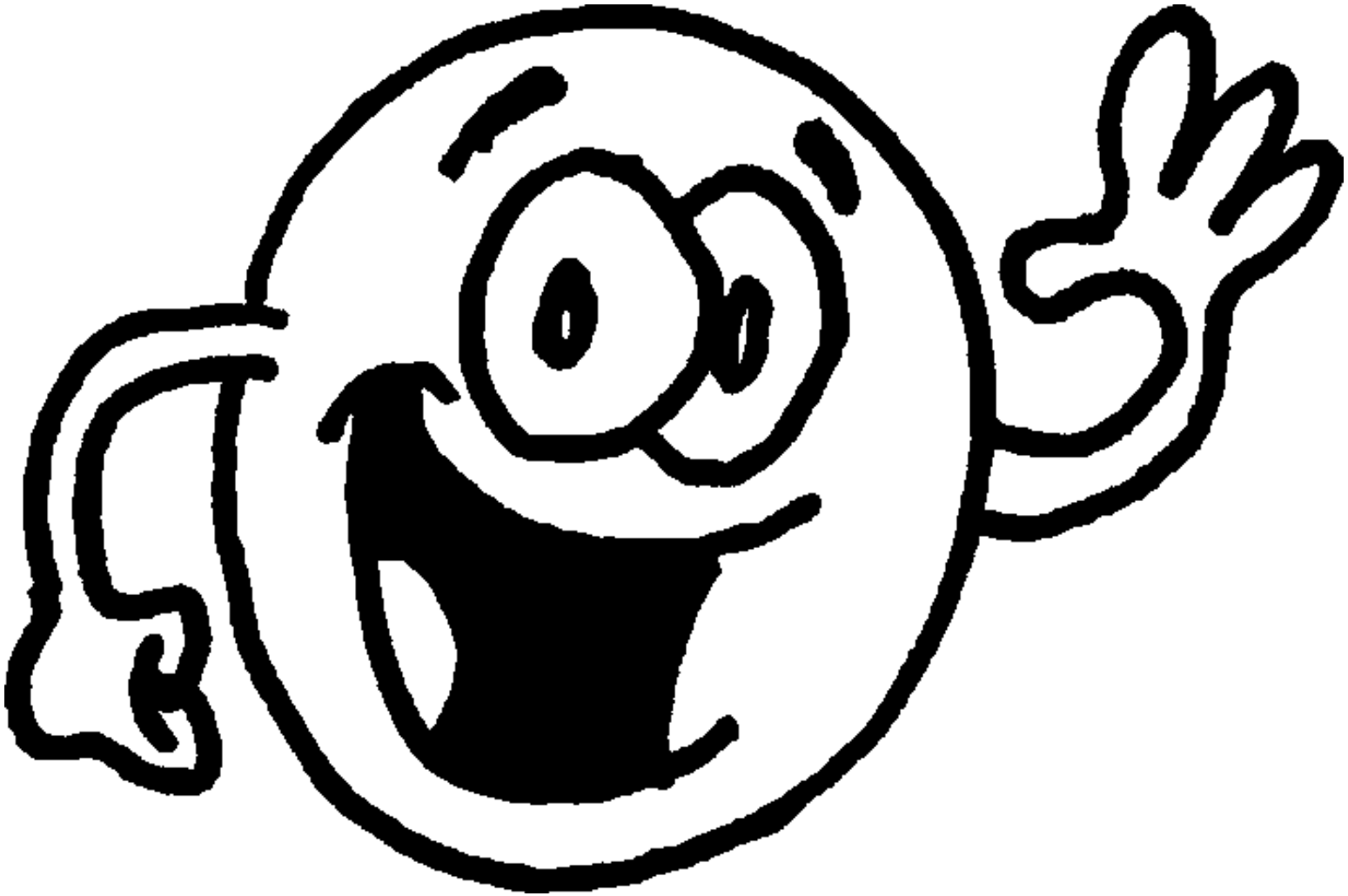
Cosmic ray propagation

Diffusion-loss equation

cosmic ray energy spectrum

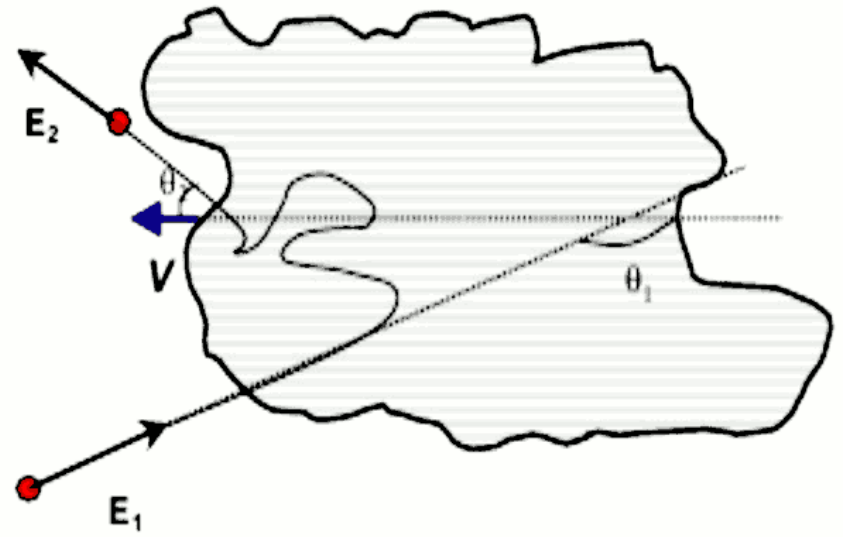
$$\frac{\partial}{\partial t}\frac{\mathrm{d}n}{\mathrm{d}\gamma}(\vec{x},\gamma) = \nabla\left[K(\vec{x},\gamma)\nabla\frac{\mathrm{d}n}{\mathrm{d}\gamma}(\vec{x},\gamma)\right] + \frac{\partial}{\partial\gamma}\left[b(\vec{x},\gamma)\frac{\mathrm{d}n}{\mathrm{d}\gamma}(\vec{x},\gamma)\right] + Q(\vec{x},\gamma)$$

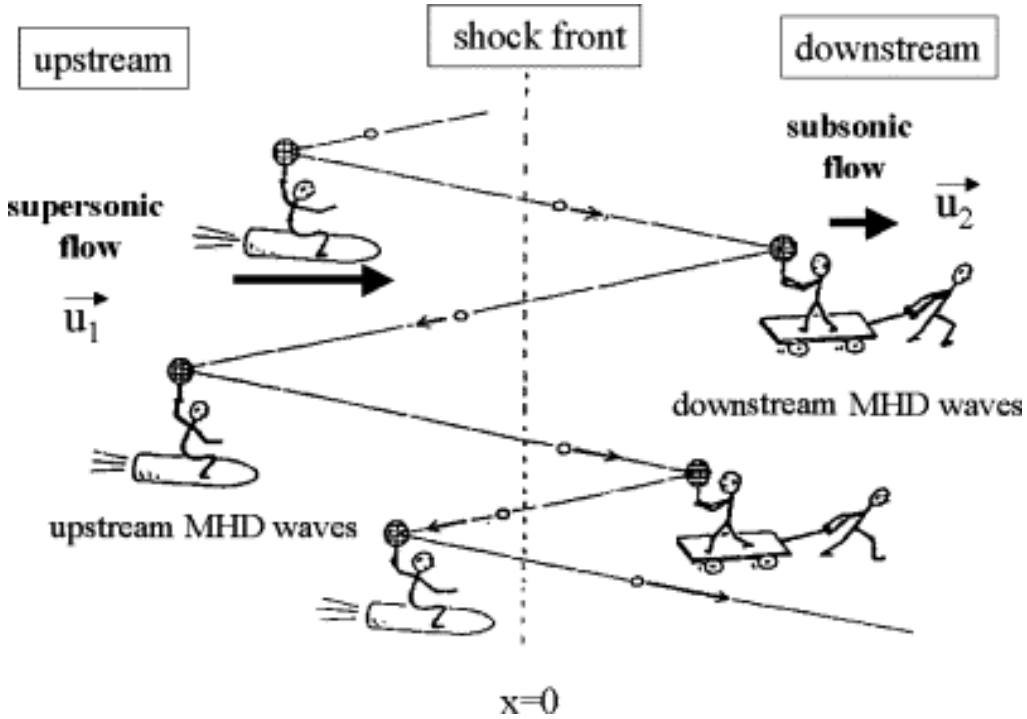
steady-state | diffusion | energy losses | source term



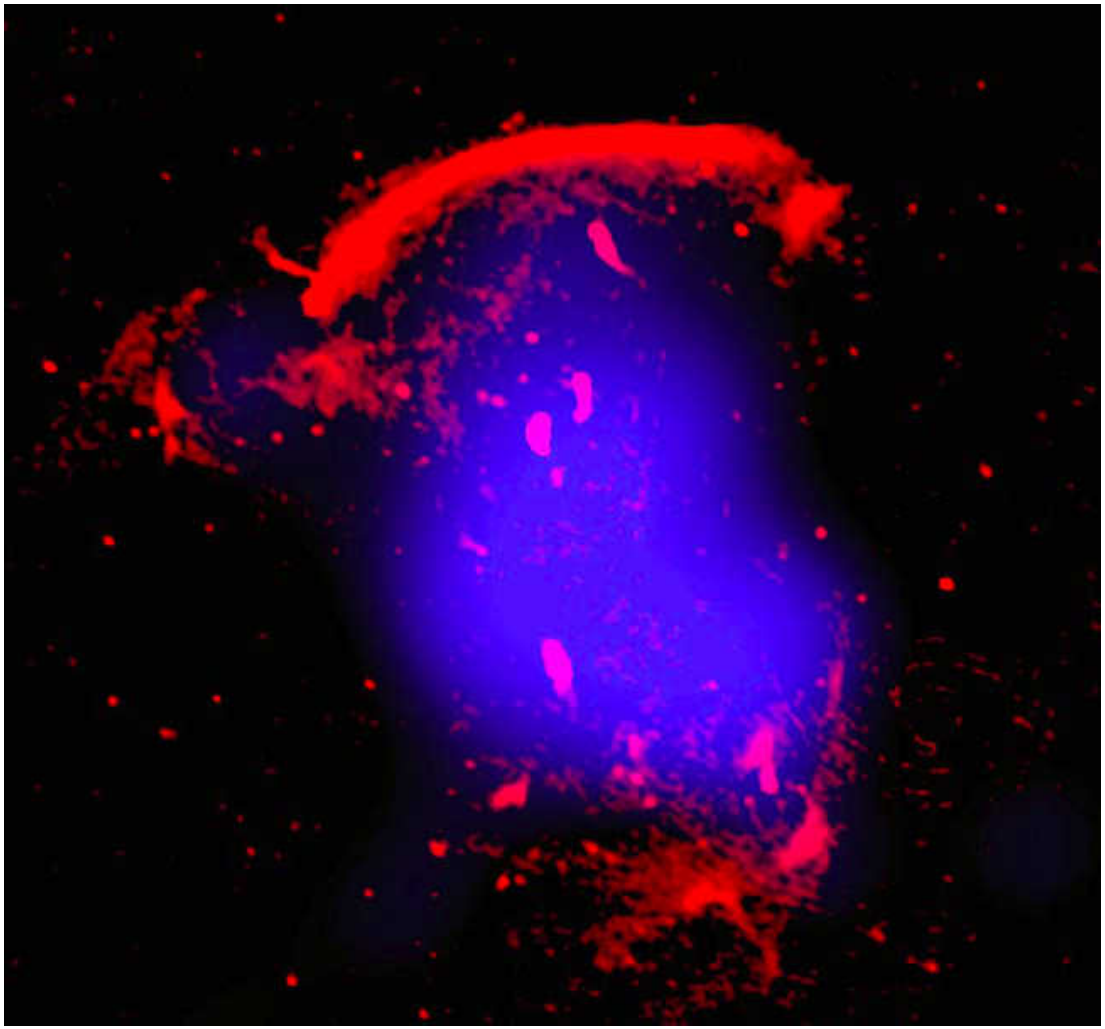
Where do the cosmic rays come from?

Fermi acceleration mechanisms

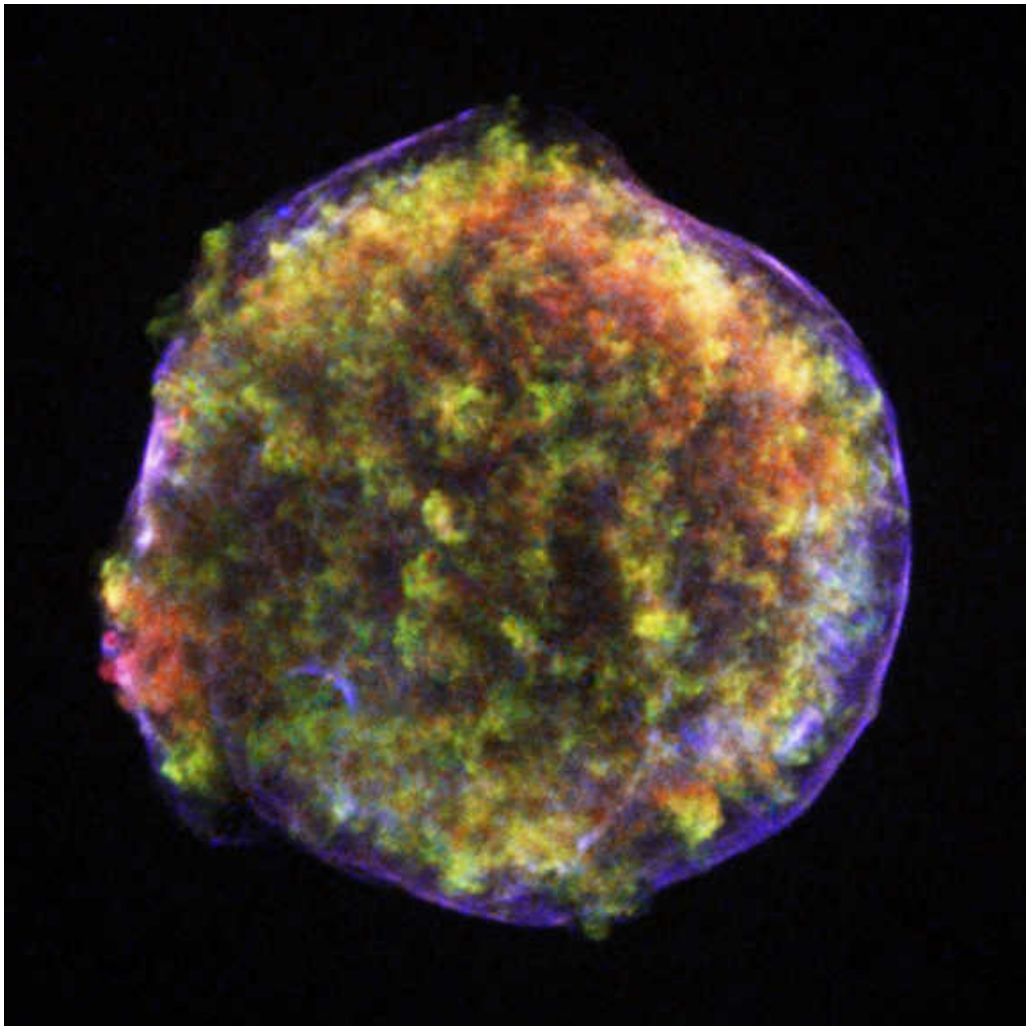




Astrophysical shocks



Supernova remnants (SNR)



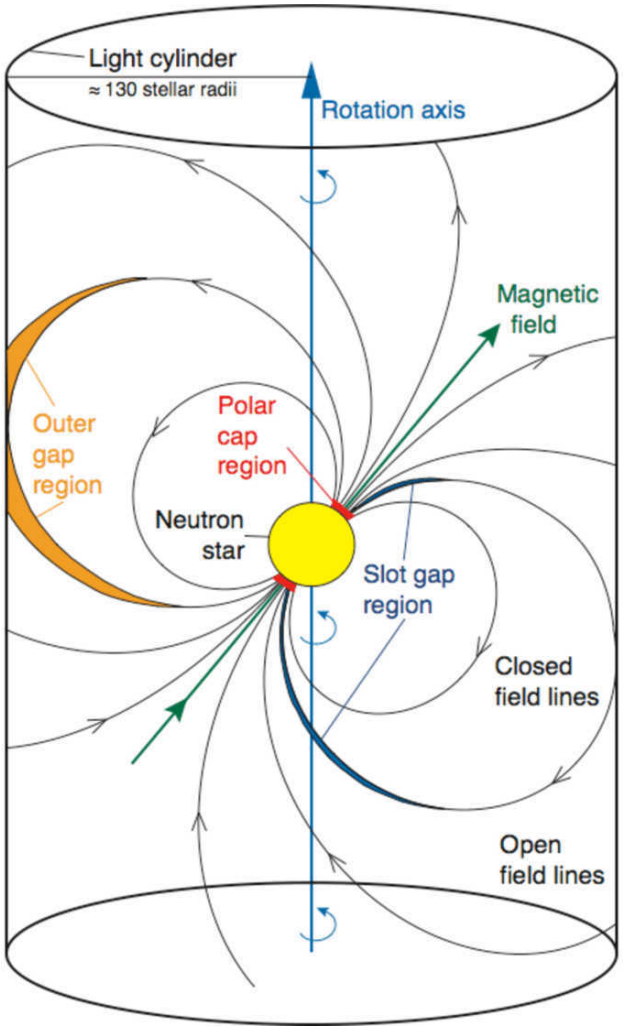
Libro del nueuo Co
META, Y DEL LV-
gar donde ſe hazẽ; y como ſe vera por las
Parallaxes quan lexos eſtan de tier-
ra; y del Prognoſtico deſte:
Compueſto por el Maeſtro Hieronymo Muñoz
Valenciano, Cathedratico de Hebreo y Mathe-
maticas en la Vniuerſidad de Valencia.

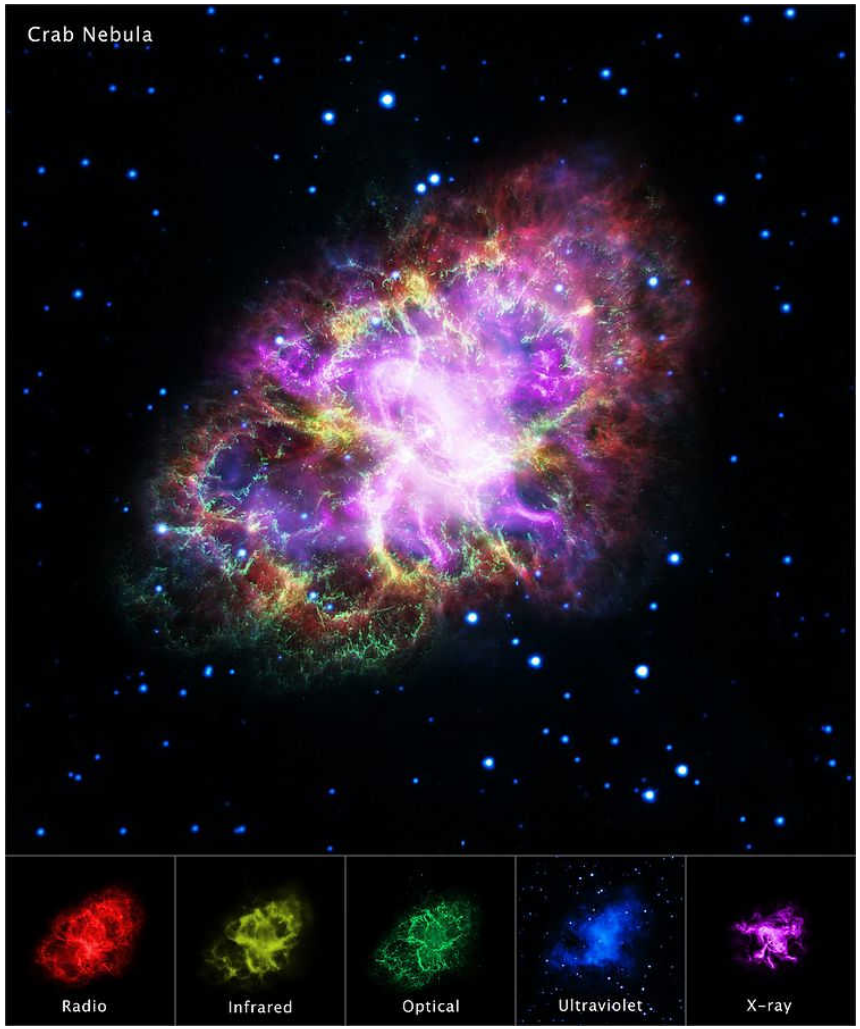
de la Libr.ª
82.

EN VALENTIA,

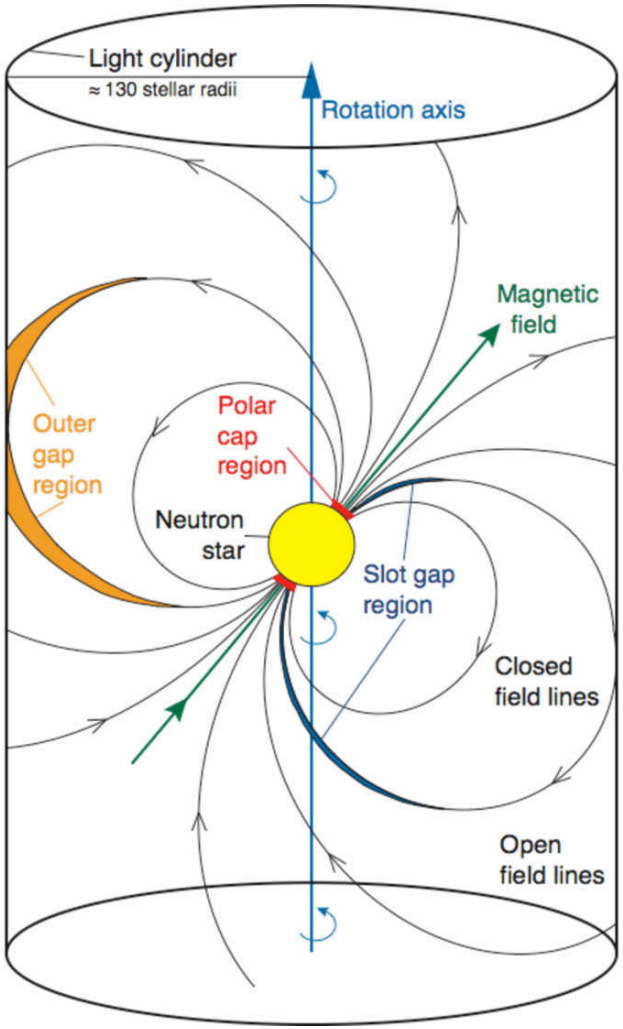
Impreſſo con licencia. en la officina de Pedro
de Huete, en la plaça de la hierba. 1573.

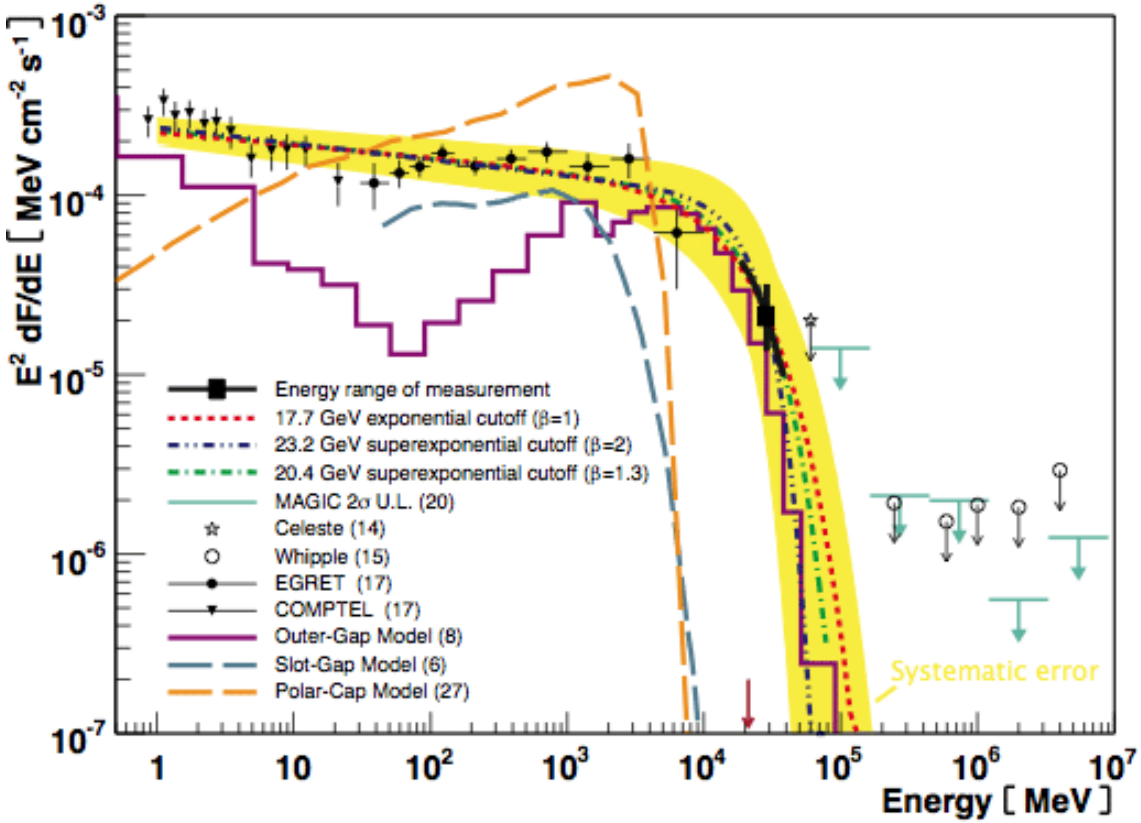
Pulsar Wind Nebulae (PWN)



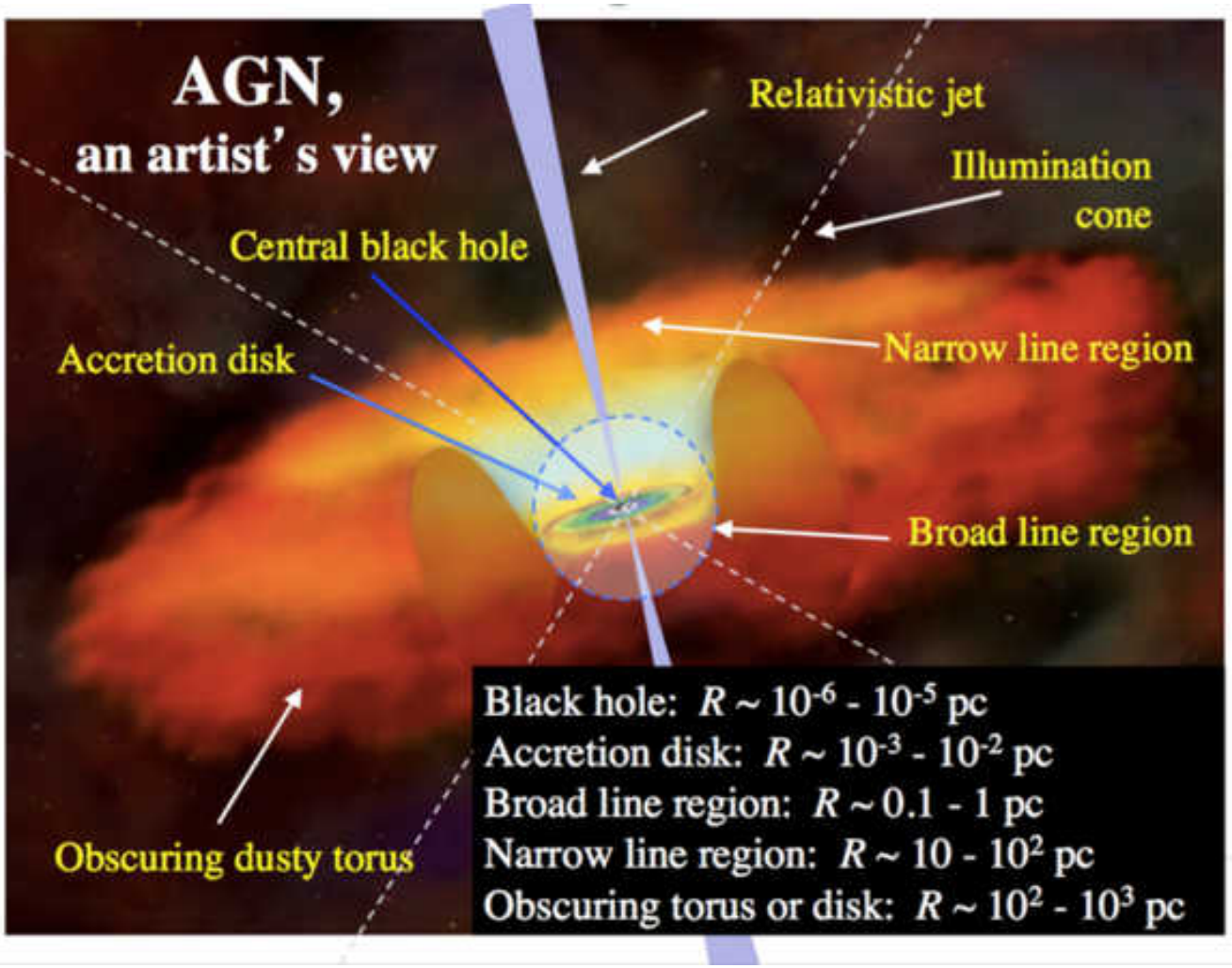


Pulsar Wind Nebulae (PWN)

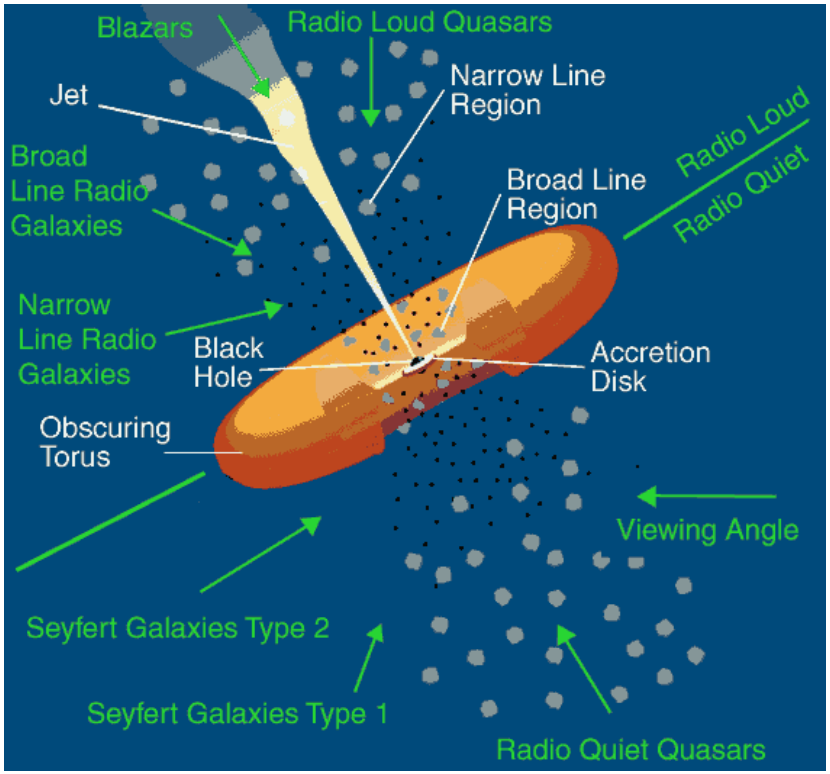


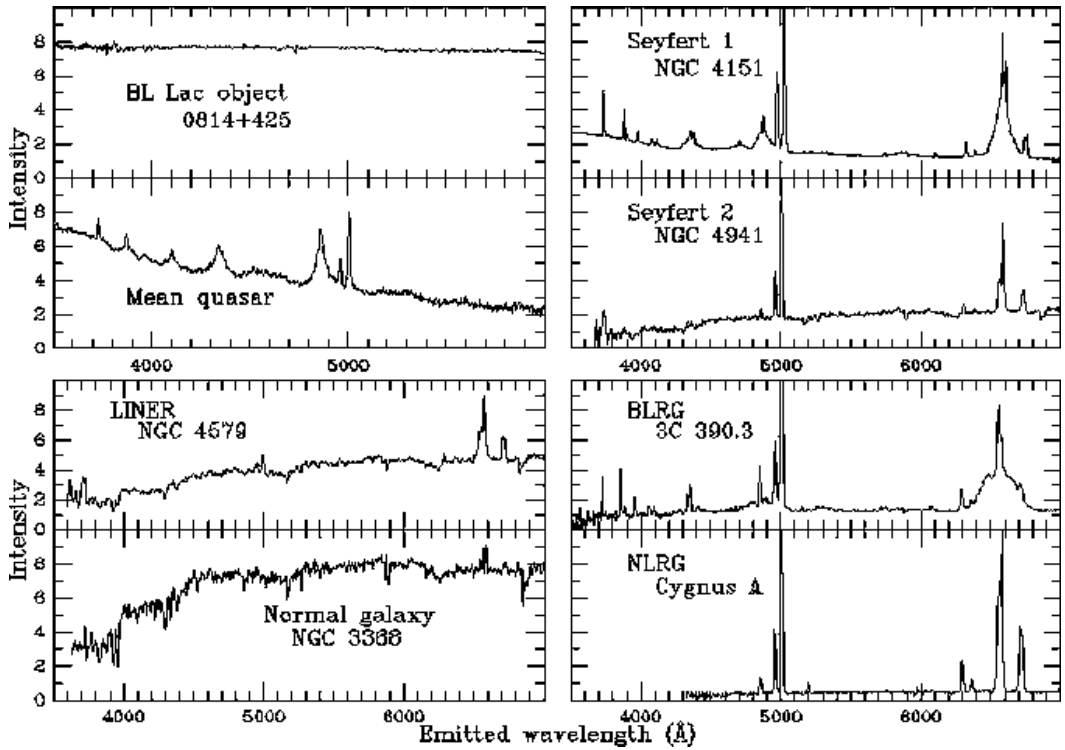


Active Galactic Nuclei (AGN)

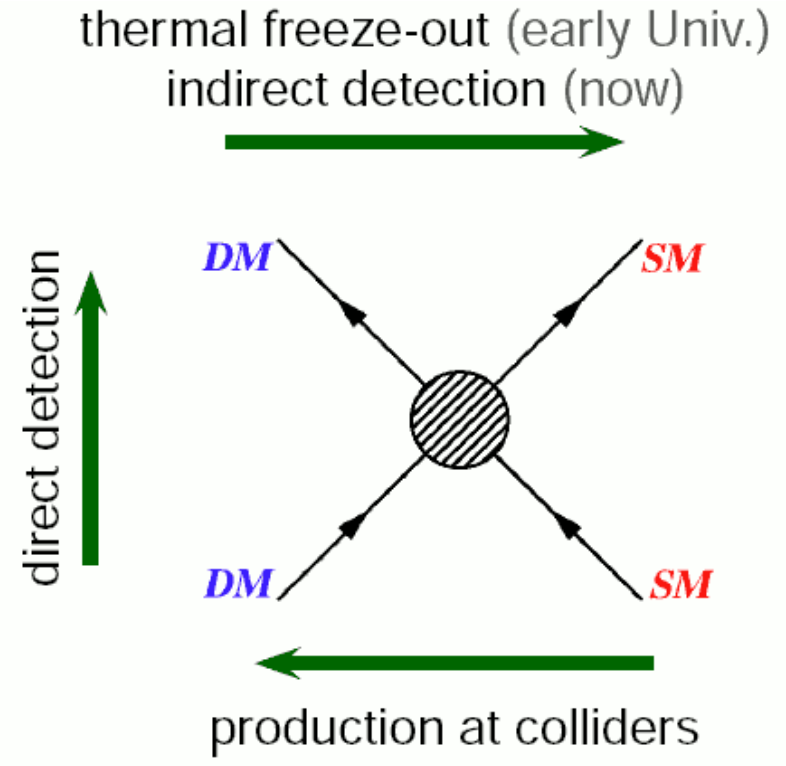


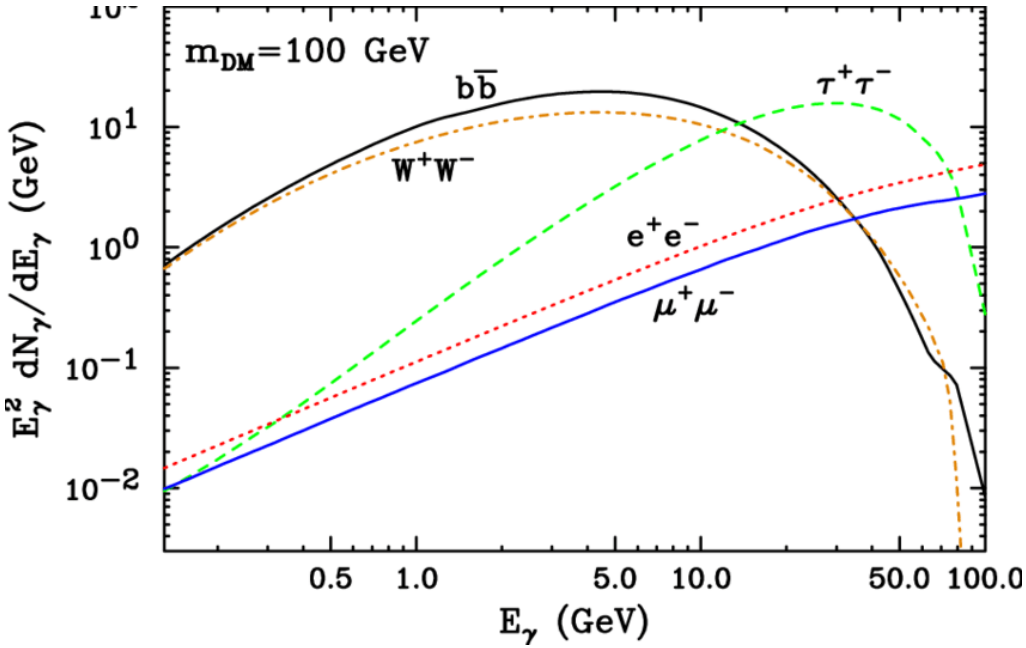
Active Galactic Nuclei (AGN)





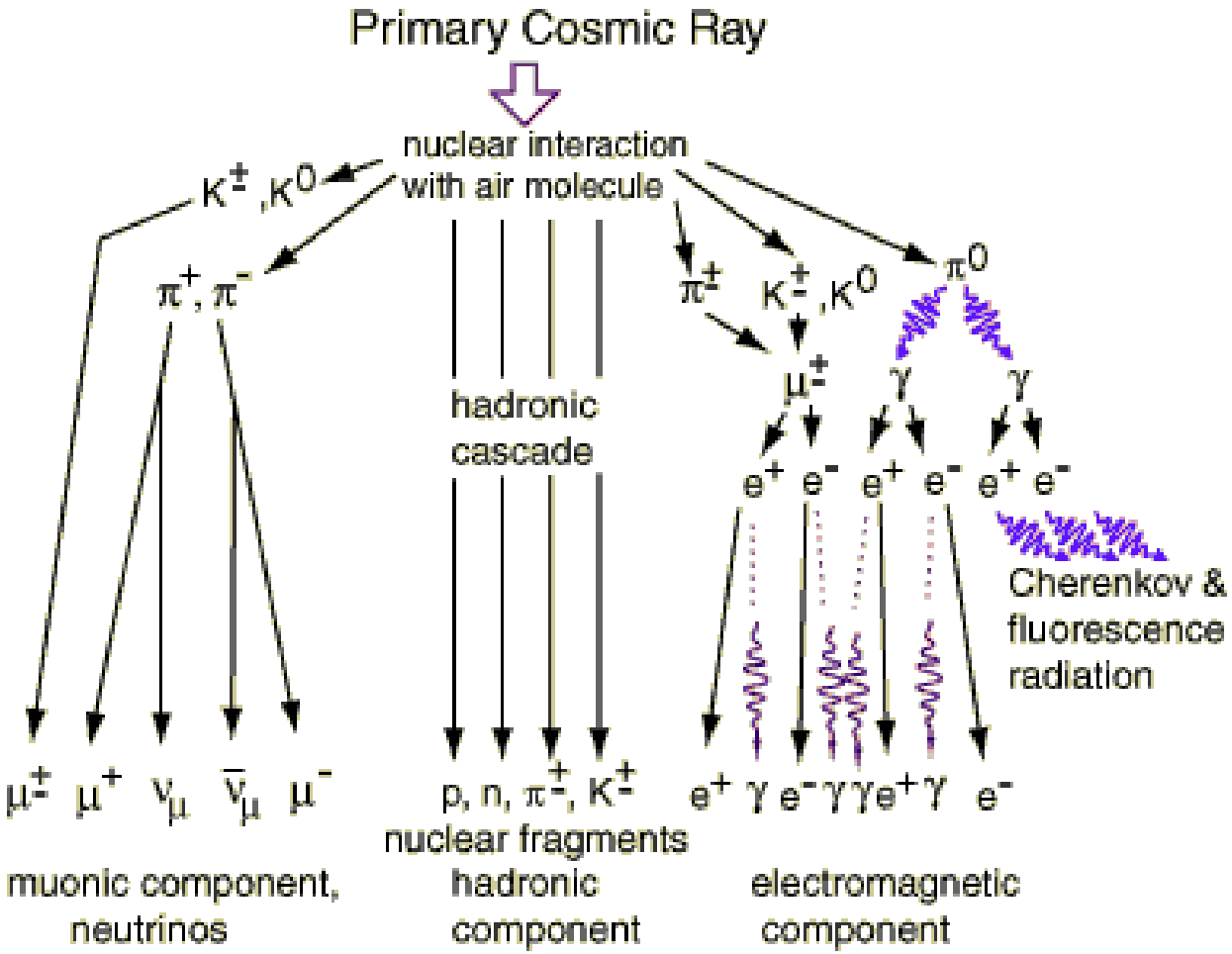
Not-so-dark matter (DM)



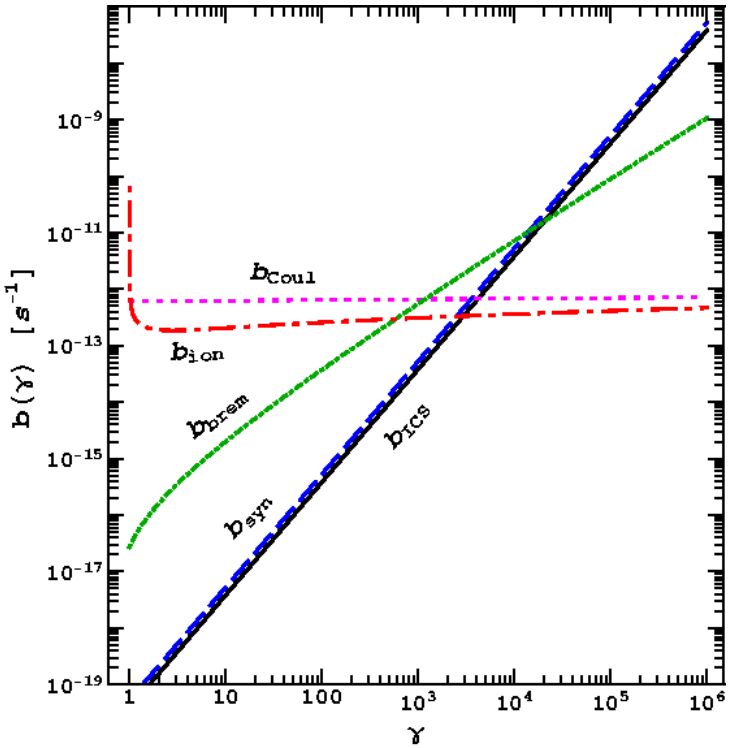


What could possibly go wrong?

Hadronic cascade



Electromagnetic losses



Ionisation

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

Inverse Compton Scattering

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

Synchrotron

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

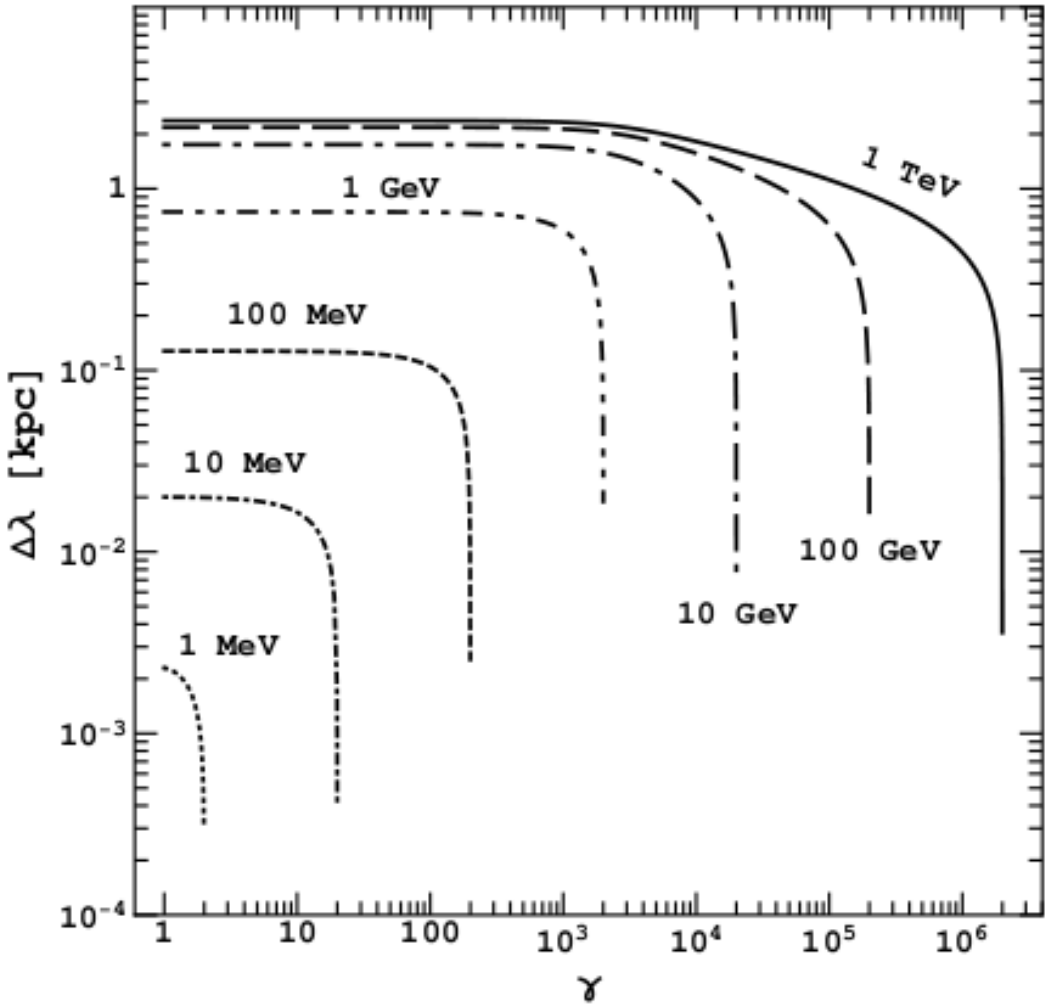
Bremsstrahlung

$$b_{\rm brem}(\gamma) \propto n_{\rm e}\gamma\,[\ln(\gamma) + 0{,}36]$$

Coulomb collisions

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

Diffusion


1 TeV
1 GeV
100 MeV
10 MeV
1 MeV
100 GeV
10 GeV
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Δλ [kpc]
1
10
100
10^3
10^4
10^5
10^6
γ

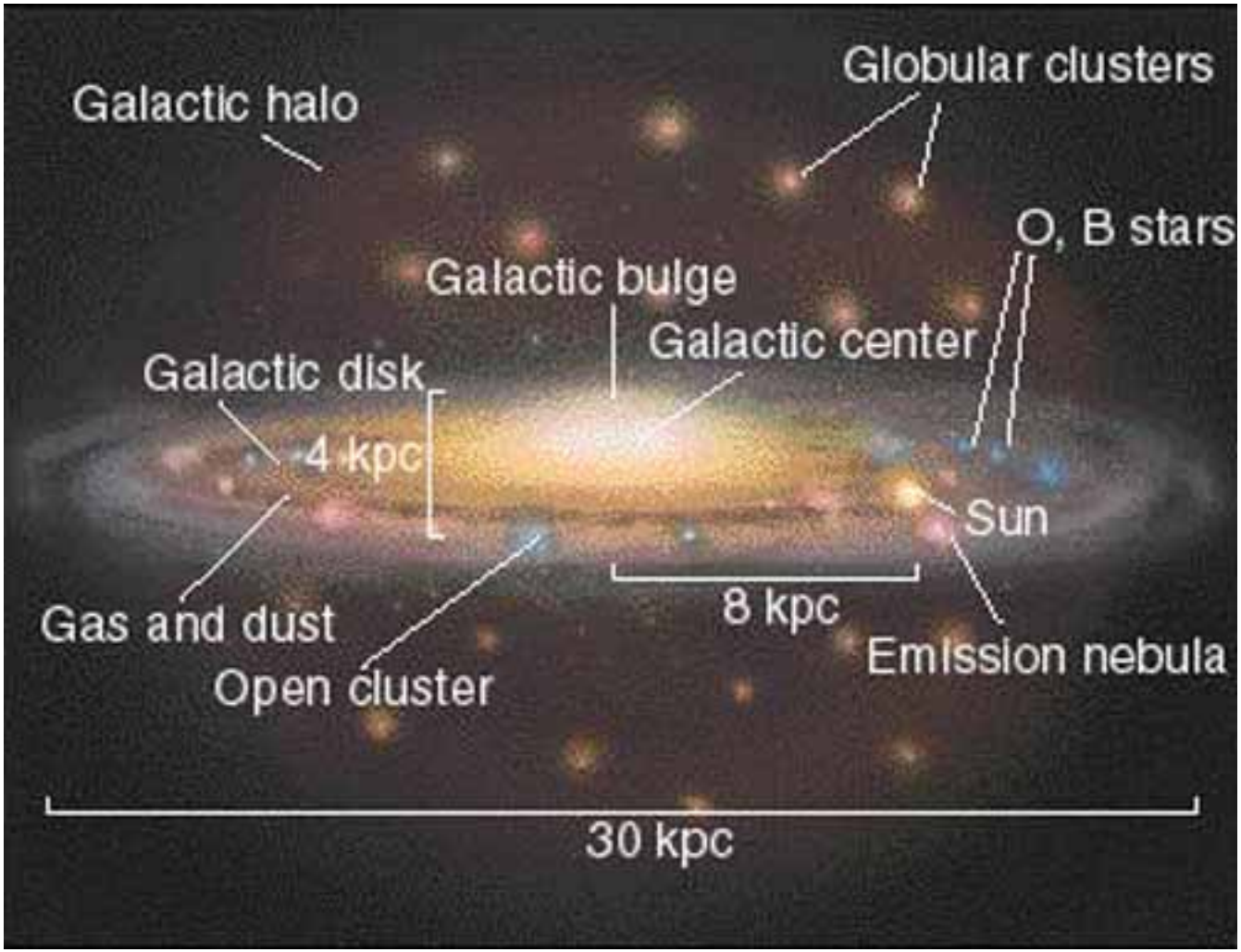
Galaxies

The Milky Way

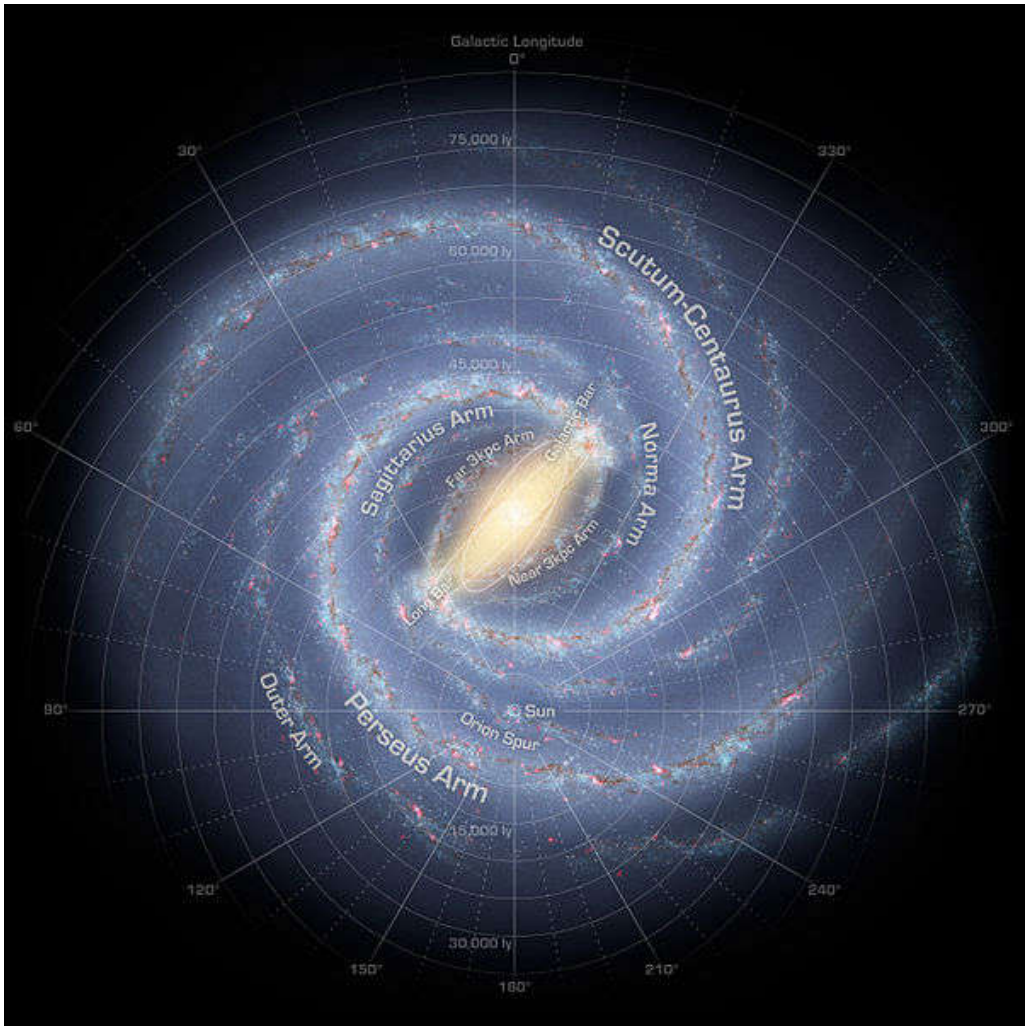
L'origine della Via Lattea, Tintoretto (1575-1580)

Aristotle (384 – 322 AC)

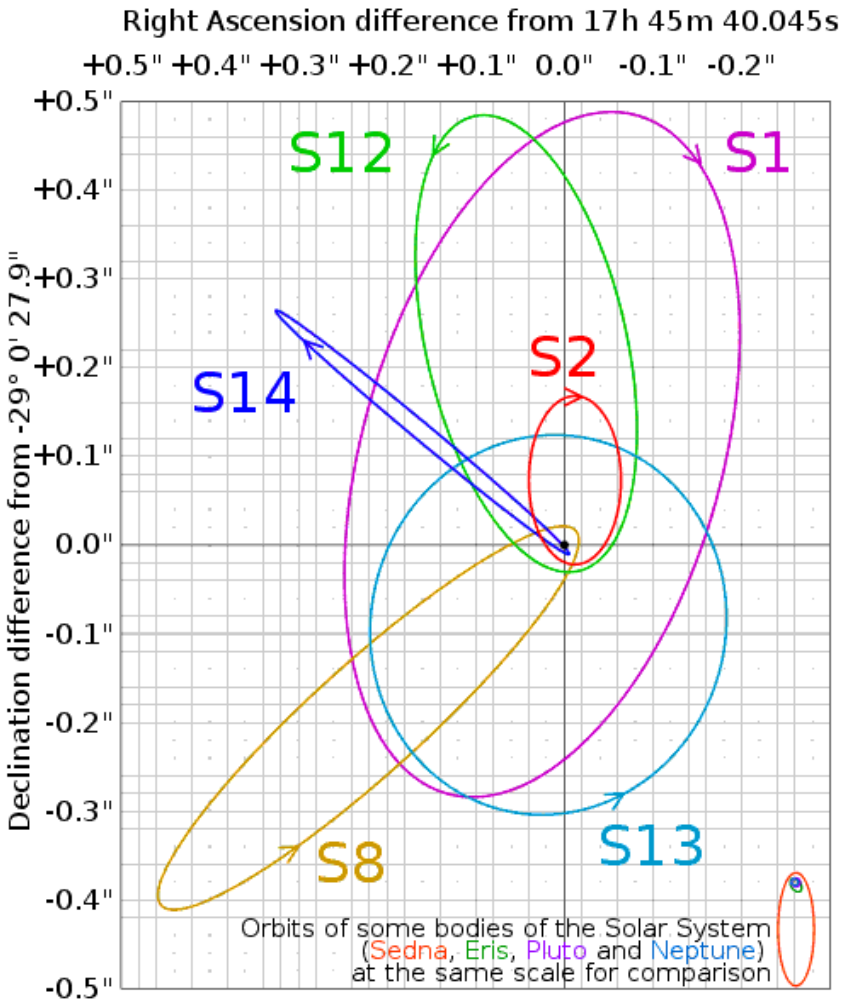
My God, it's full of stars!



My God, it's full of stars!



The Galactic nucleus

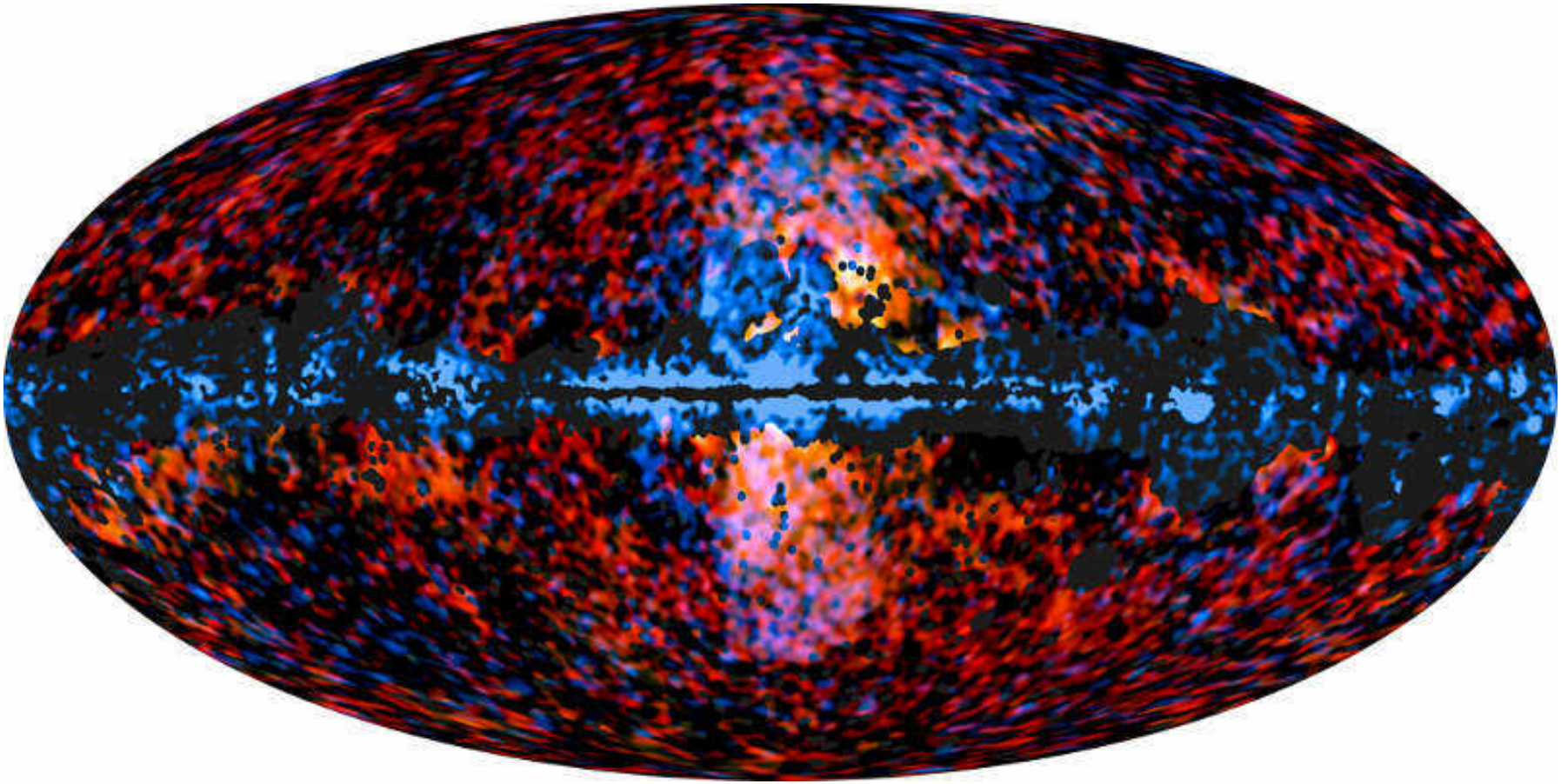


Mass of Sagittarius A*

$$\sim 10^6\ \mathrm{M}_\odot$$

The Galactic nucleus

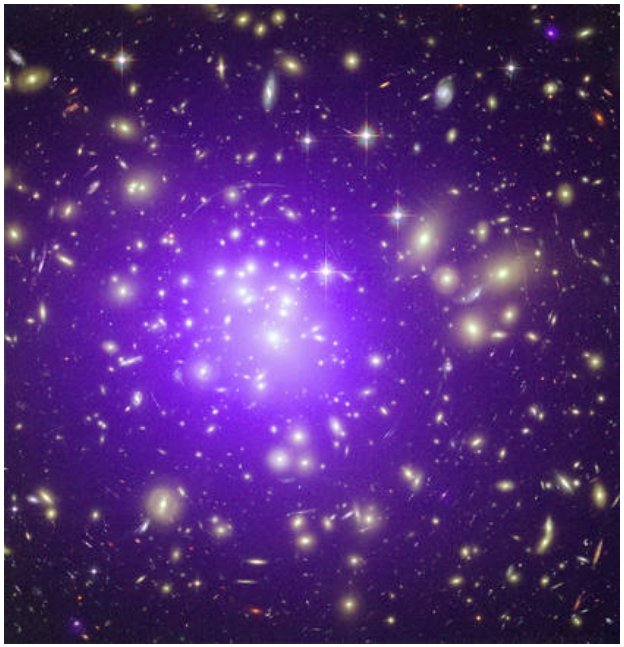
The Galactic nucleus



The Interstellar Medium (ISM)

Pressure

$$\nabla P = -\rho \nabla \phi$$



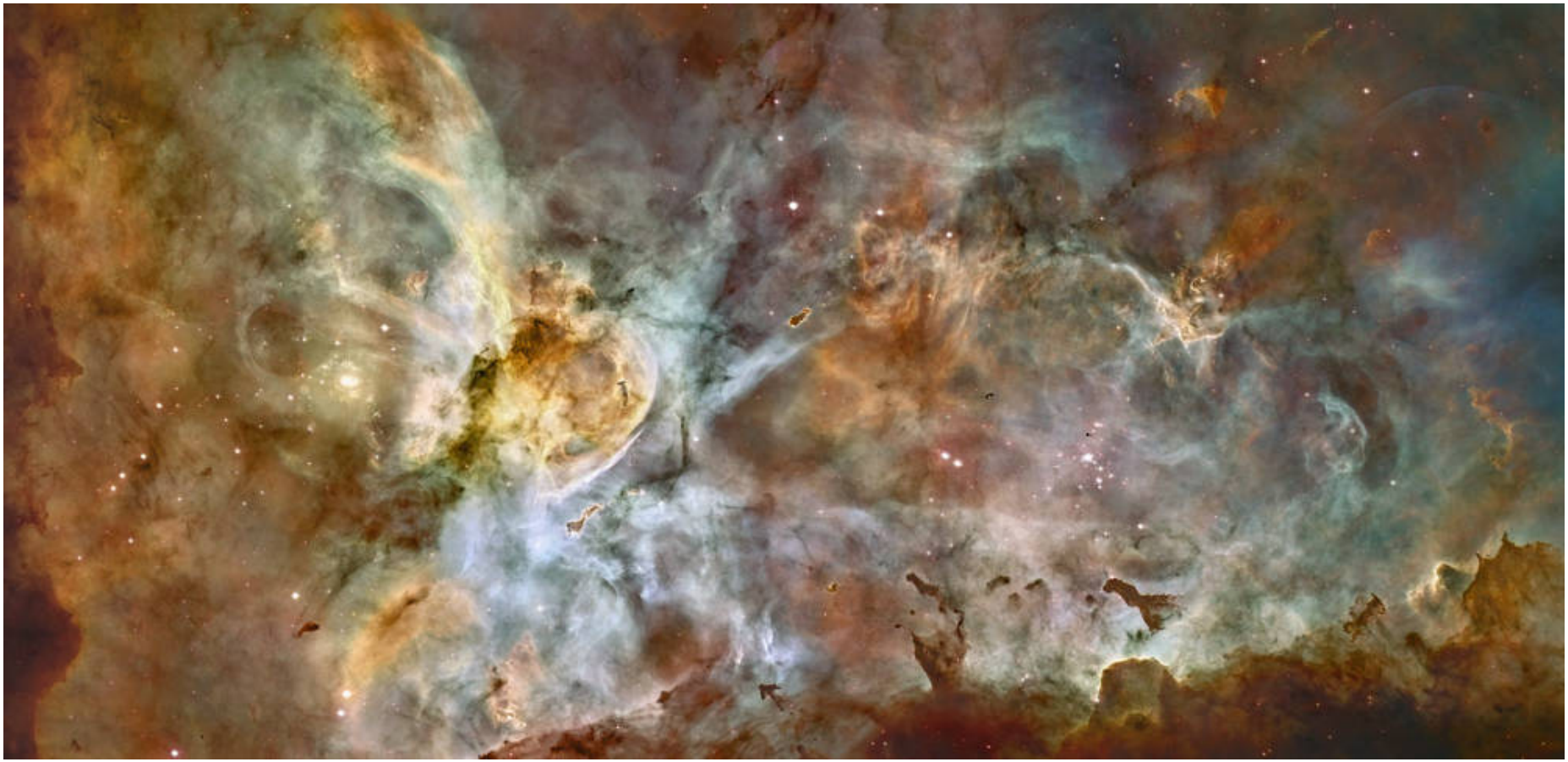
Hot spherical halo

Angular momentum

$$V_{tg}/R = -\nabla \phi$$

Cold rotating disk

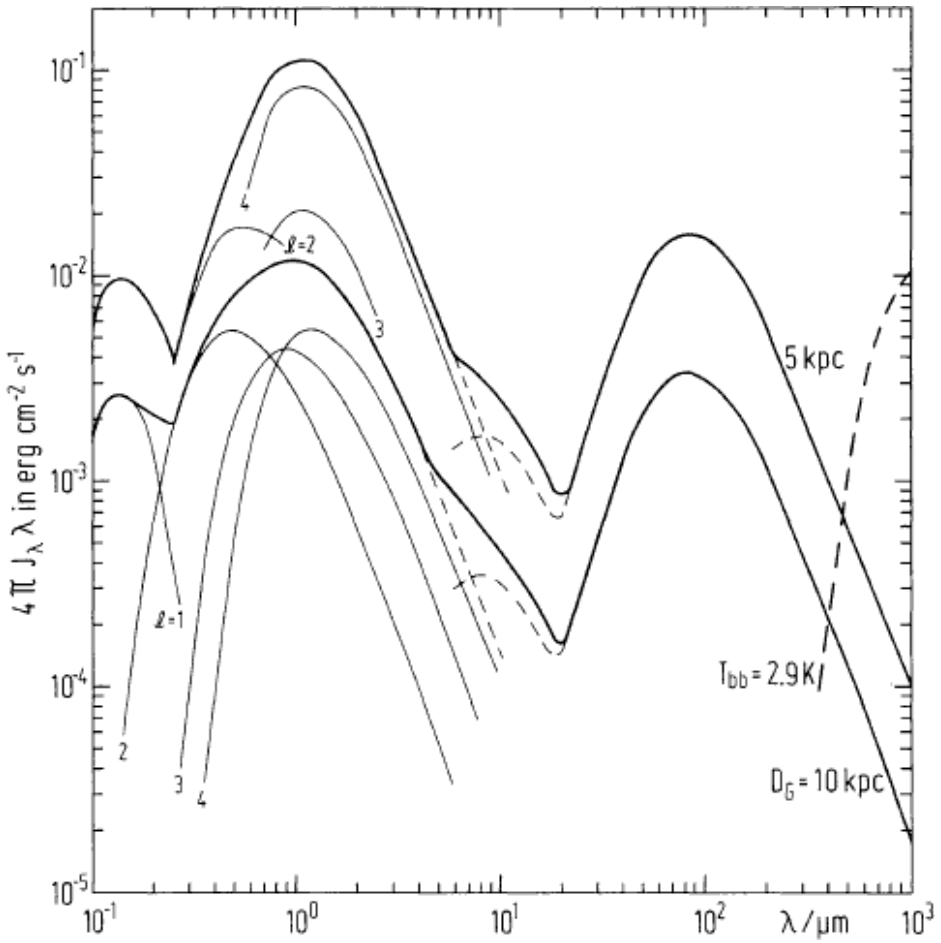
The Interstellar Medium (ISM)



The Interstellar Medium (ISM)

Phase	f_v	f_m	h (pc)	T (K)	n (cm^{-3})
Molecular clouds	1 %	22 %	80	15	> 100
Cold neutral medium	3 %	30 %	150	70	30
Warm neutral medium	20 %	35 %	400	8000	1
Warm ionised medium	30 %	10 %	1000	8000	1
HII regions	1 %	1 %	70	8000	> 100
Hot ionised medium	45 %	2 %	> 1000	$> 10^5$	$< 0{,}01$

The Interstellar Radiation Field (ISRF)

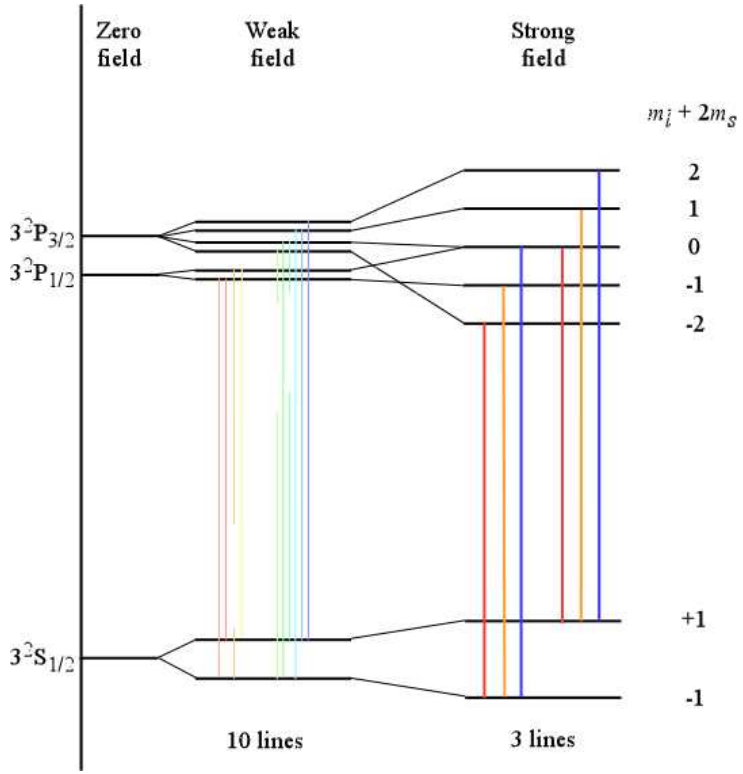


Mathis et al. (1983)

Magnetic field

Detection

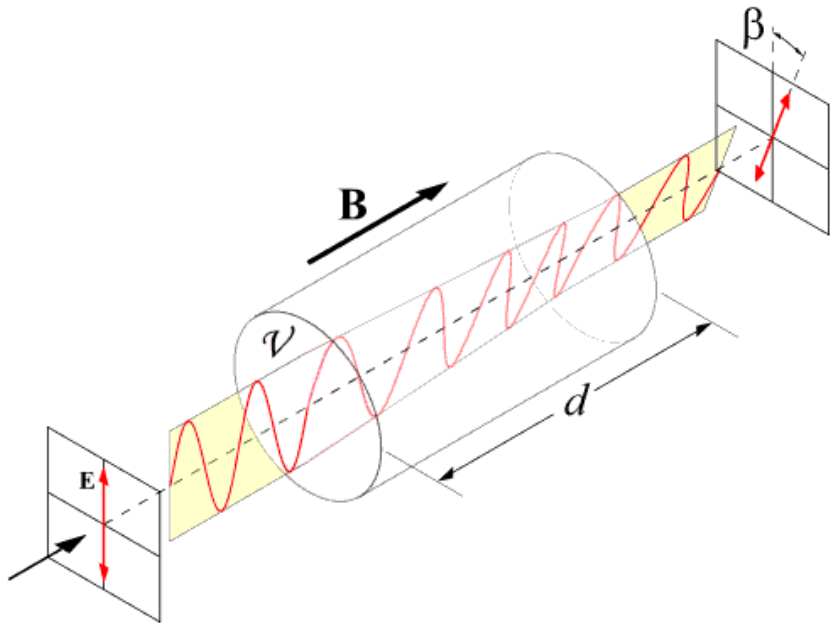
- Zeeman effect
- Faraday rotation
- Synchrotron emission
  - intensity
  - polarization
- Light polarization
  - of starlight, by dust
  - of the dust emission



Magnetic field

Detection

- Zeeman effect
- Faraday rotation
- Synchrotron emission
  - intensity
  - polarization
- Light polarization
  - of starlight, by dust
  - of the dust emission

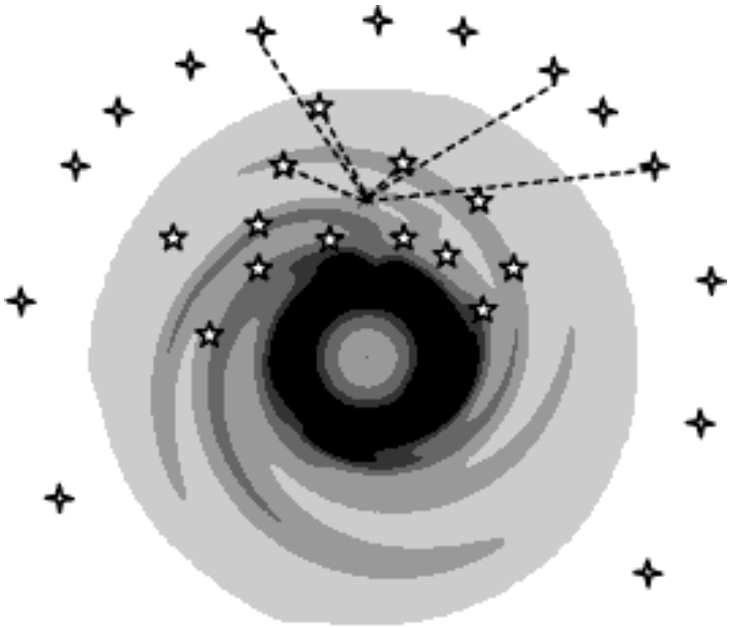


$$\beta \propto \lambda^2 \int n_e B_{\parallel} \, \mathrm{d}s$$

Magnetic field

Detection

- Zeeman effect
- Faraday rotation
- Synchrotron emission
  - intensity
  - polarization
- Light polarization
  - of starlight, by dust
  - of the dust emission

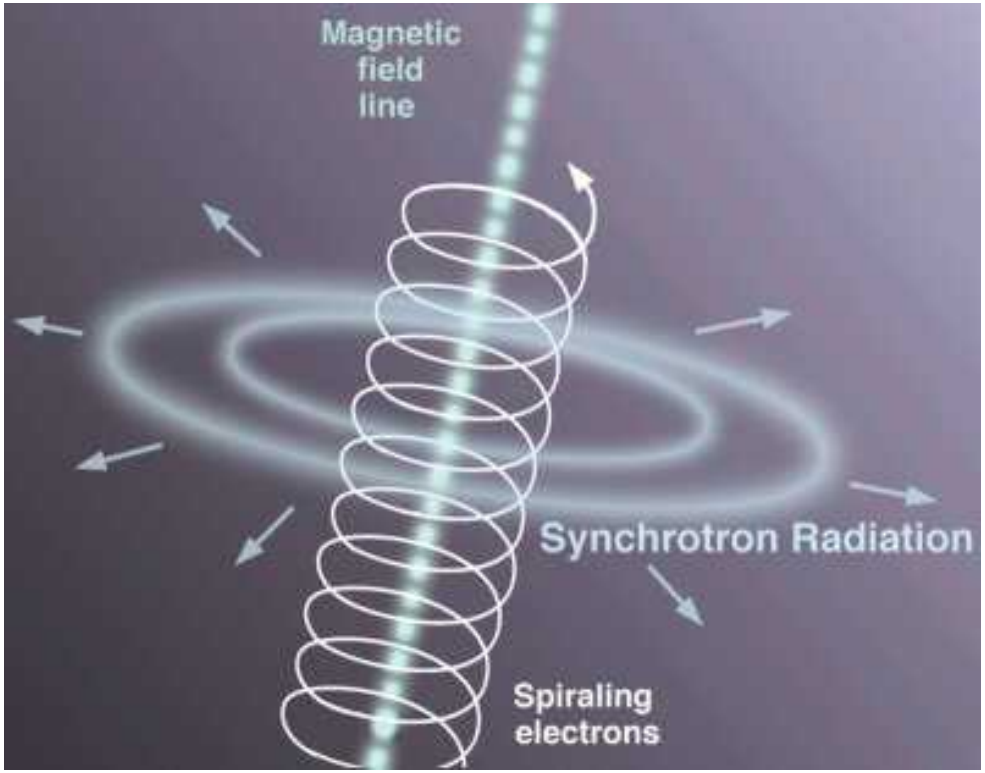


$$\beta \propto \lambda^2 \int n_e B_{\parallel} \, \mathrm{d}s$$

Magnetic field

Detection

- Zeeman effect
- Faraday rotation
- Synchrotron emission
  - intensity
  - polarization
- Light polarization
  - of starlight, by dust
  - of the dust emission

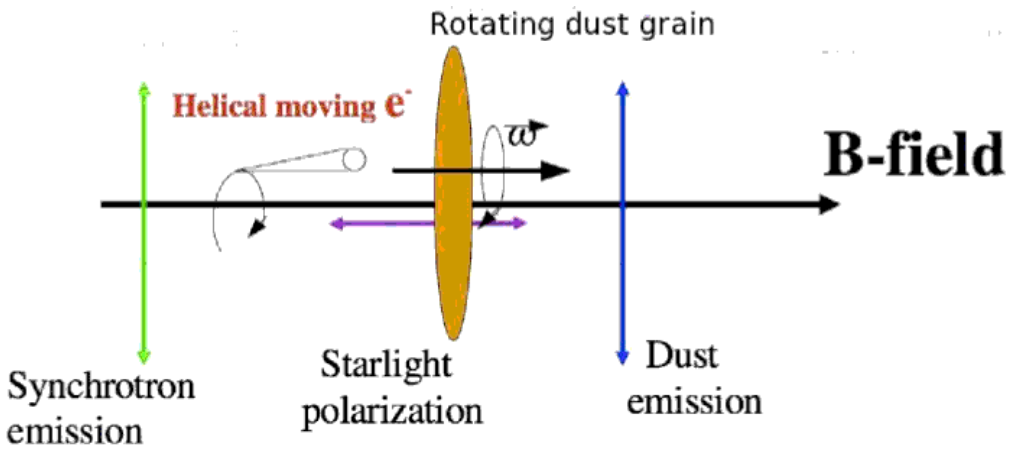


$$I_{\rm syn} \propto \int n_{\rm e} B_{\perp} \, {\rm d}s$$

Magnetic field

Detection

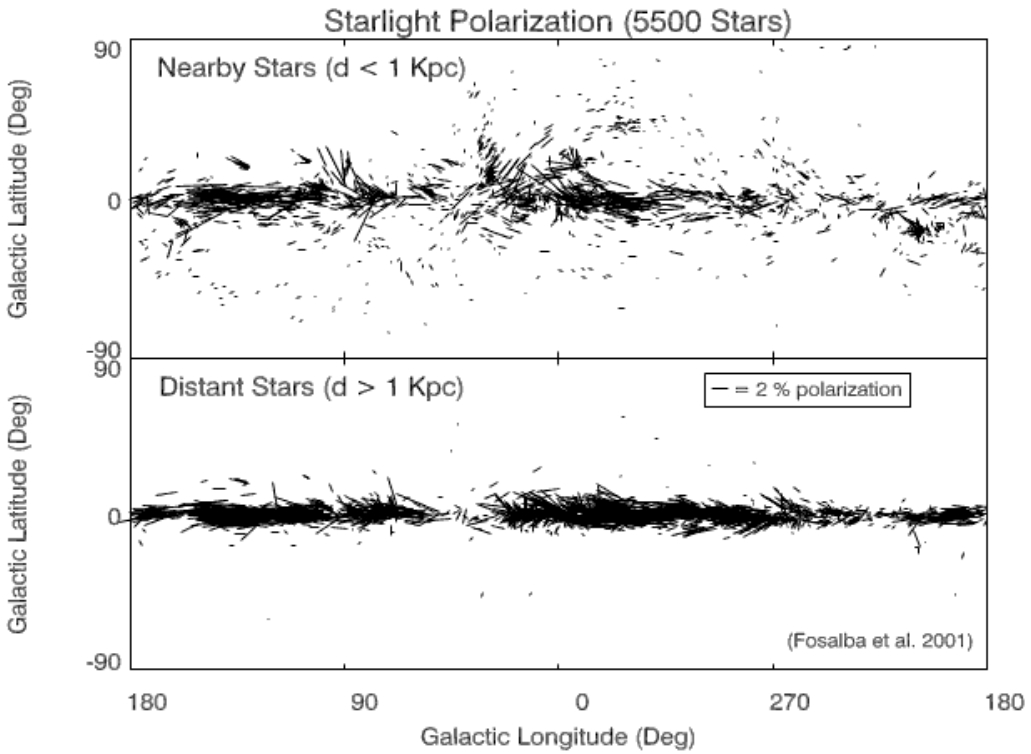
- Zeeman effect
- Faraday rotation
- Synchrotron emission
  - intensity
  - polarization
- Light polarization
  - of starlight, by dust
  - of the dust emission



Magnetic field

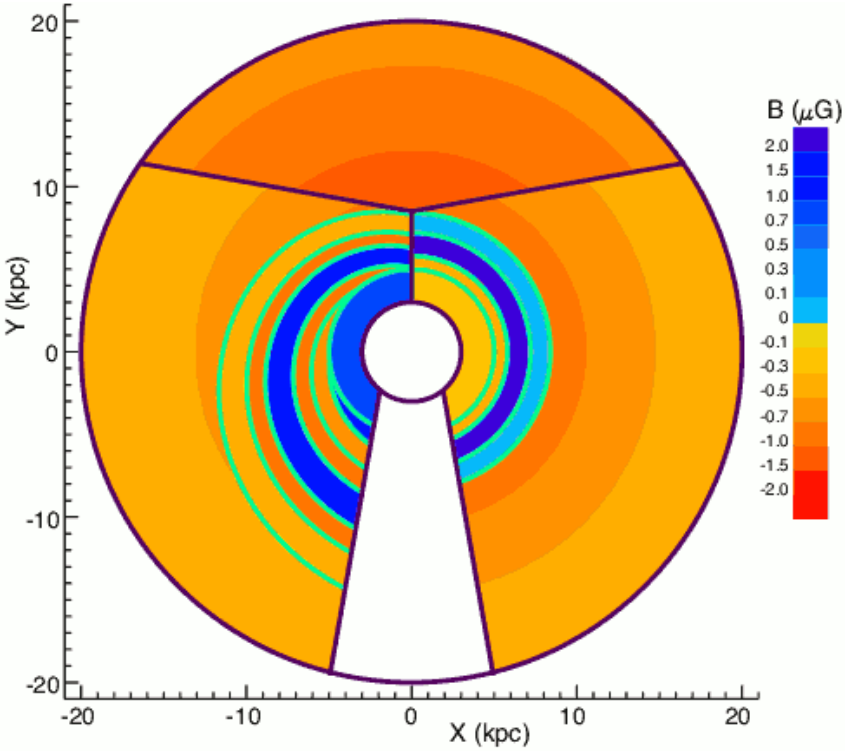
Detection

- Zeeman effect
- Faraday rotation
- Synchrotron emission
  - intensity
  - polarization
- Light polarization
  - of starlight, by dust
  - of the dust emission

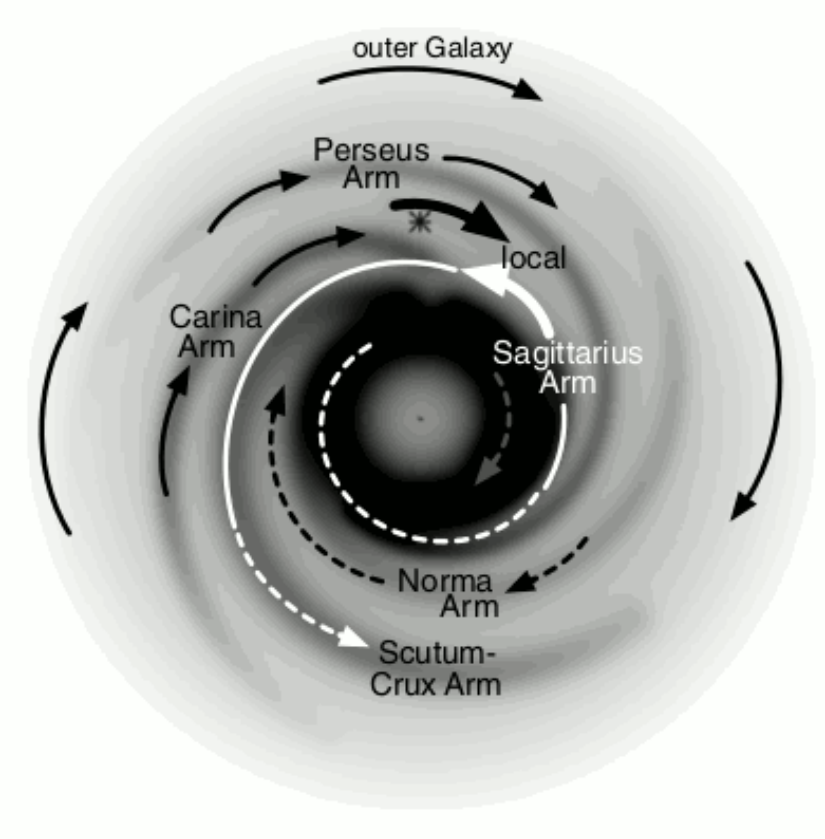


Fosalba et al. (2002)

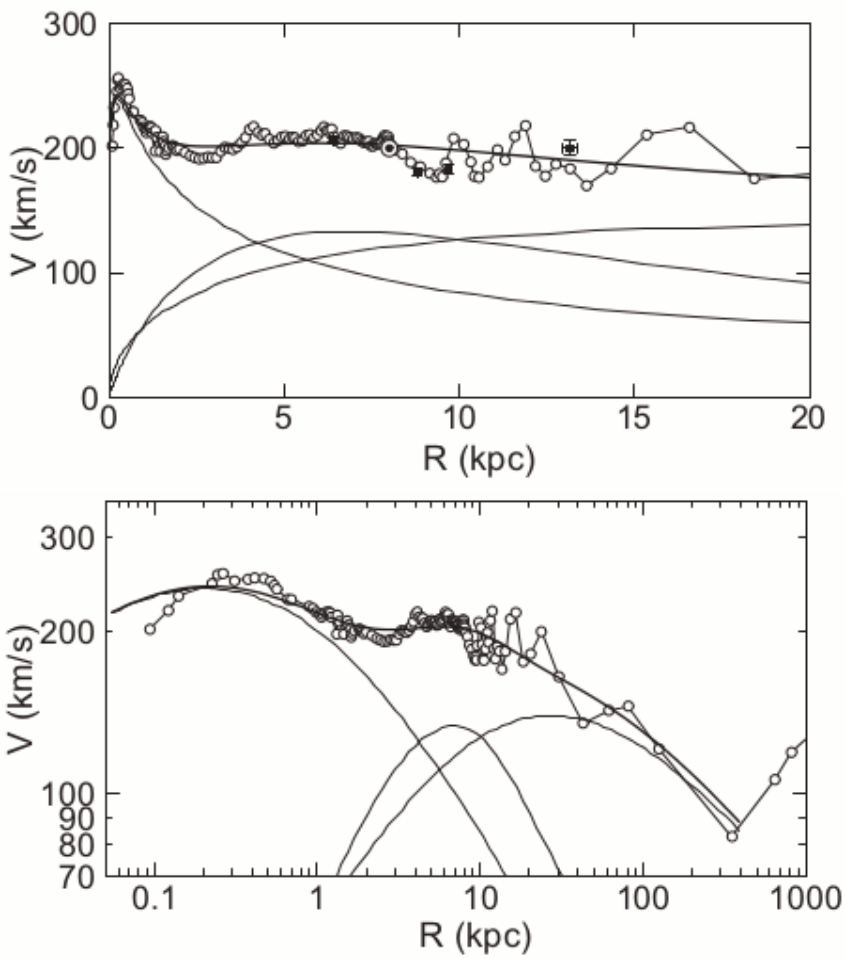
Magnetic field



Van Eck et al. (2011)



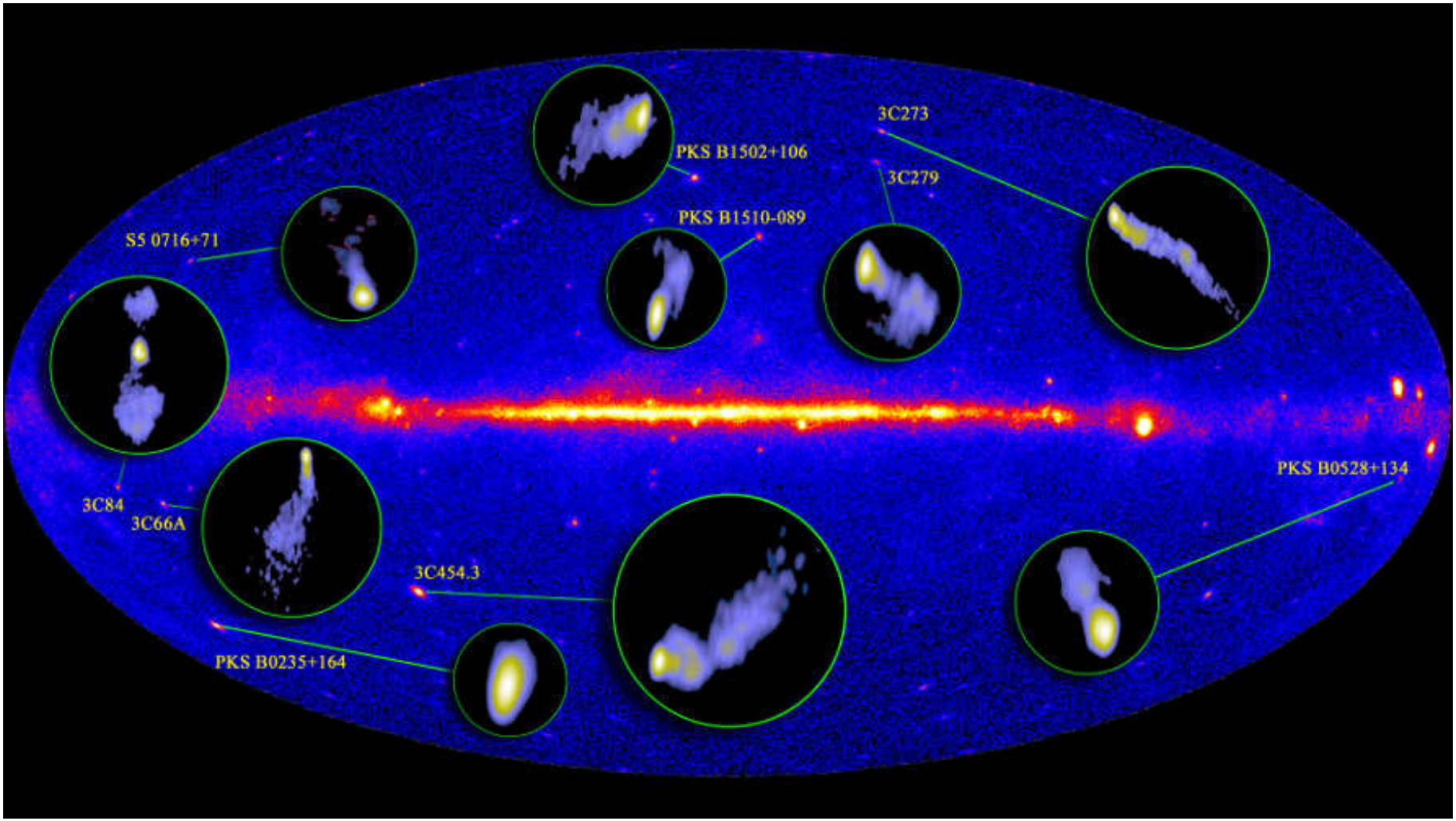
Dark matter



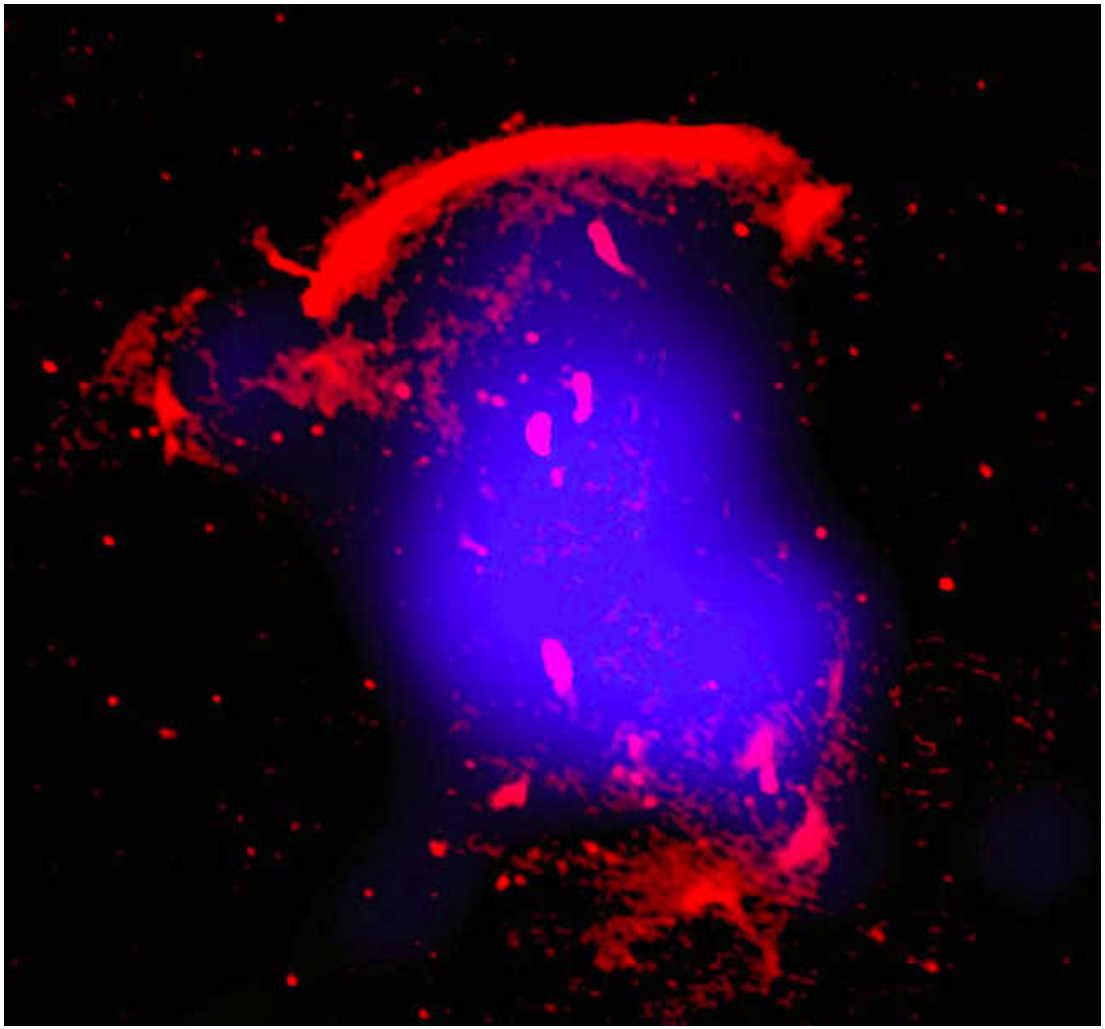
Sofue (2012)


ASK ME
© Paws, Inc.
IF I CARE

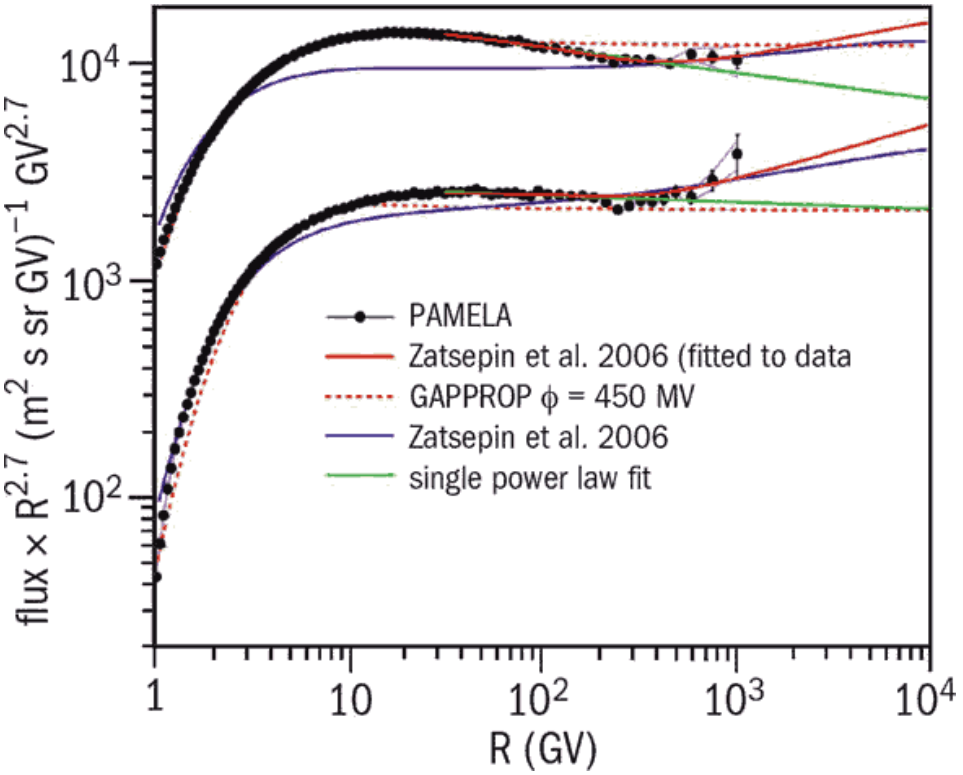
Radio and gamma-ray emission



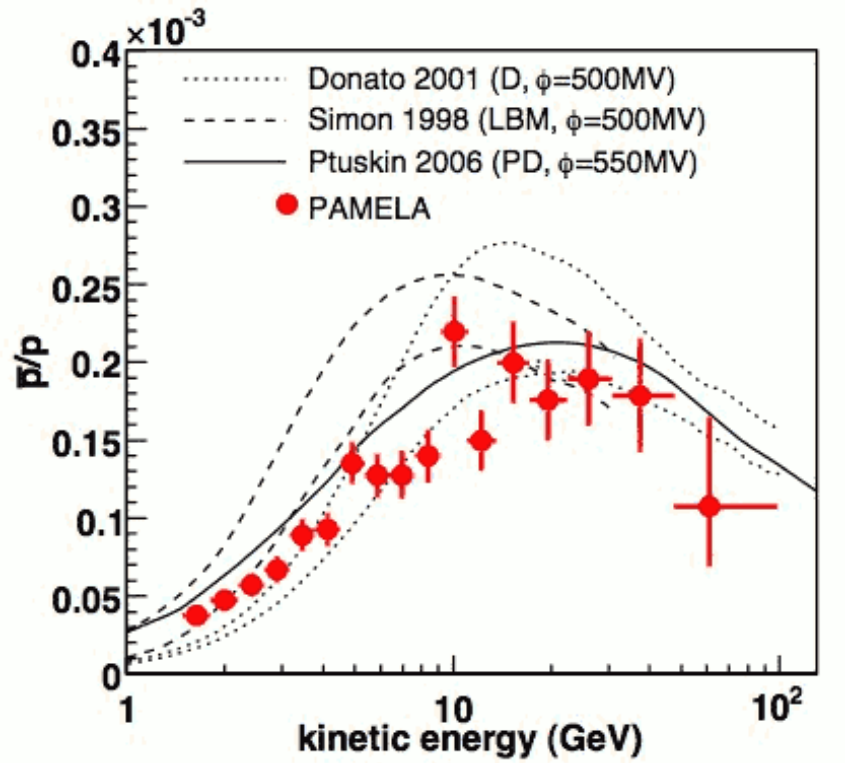
Radio and gamma-ray emission



Cosmic ray spectrum

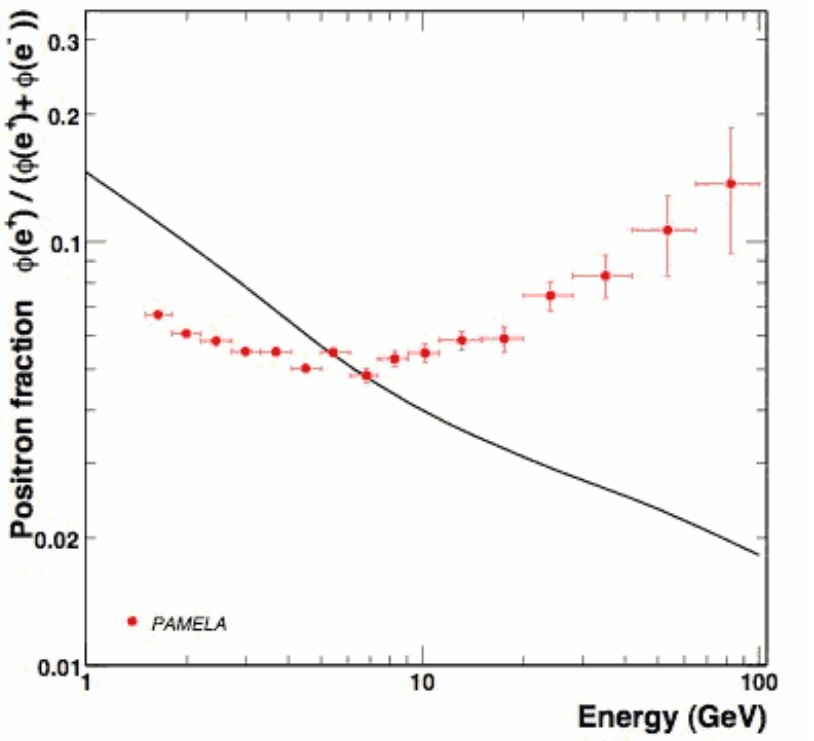


Adriani et al. (2011)

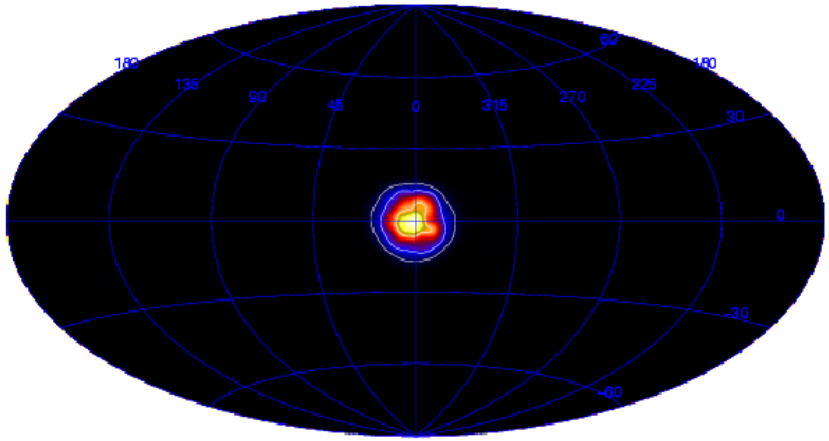


Adriani et al. (2009a)

Cosmic ray spectrum

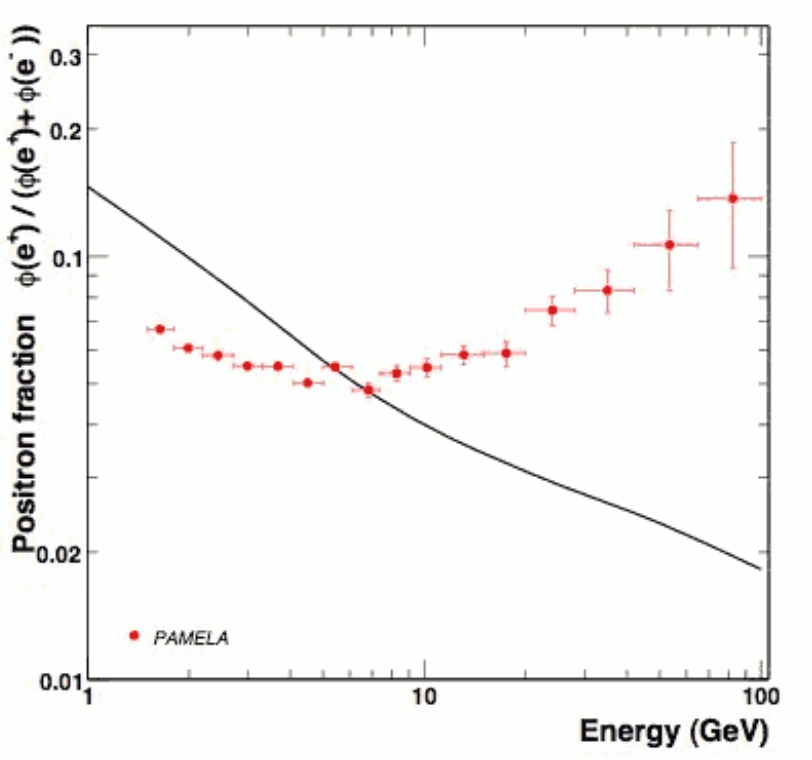


Adriani et al. (2009b)

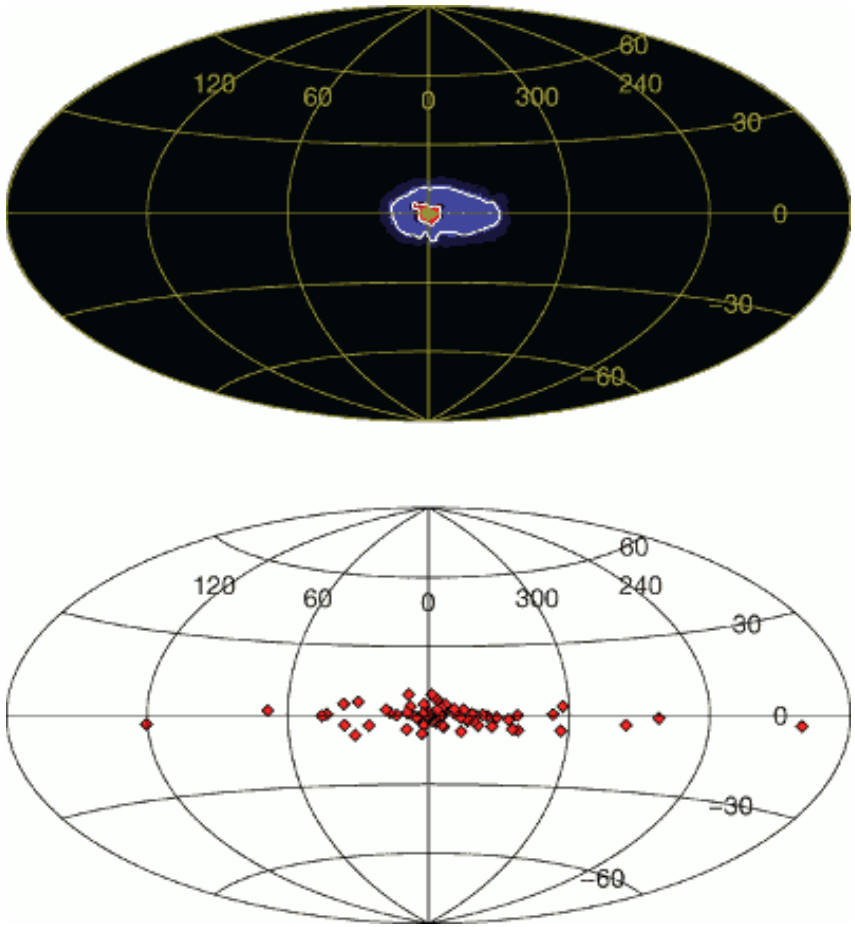


Knödlseder et al. (2005)

Cosmic ray spectrum

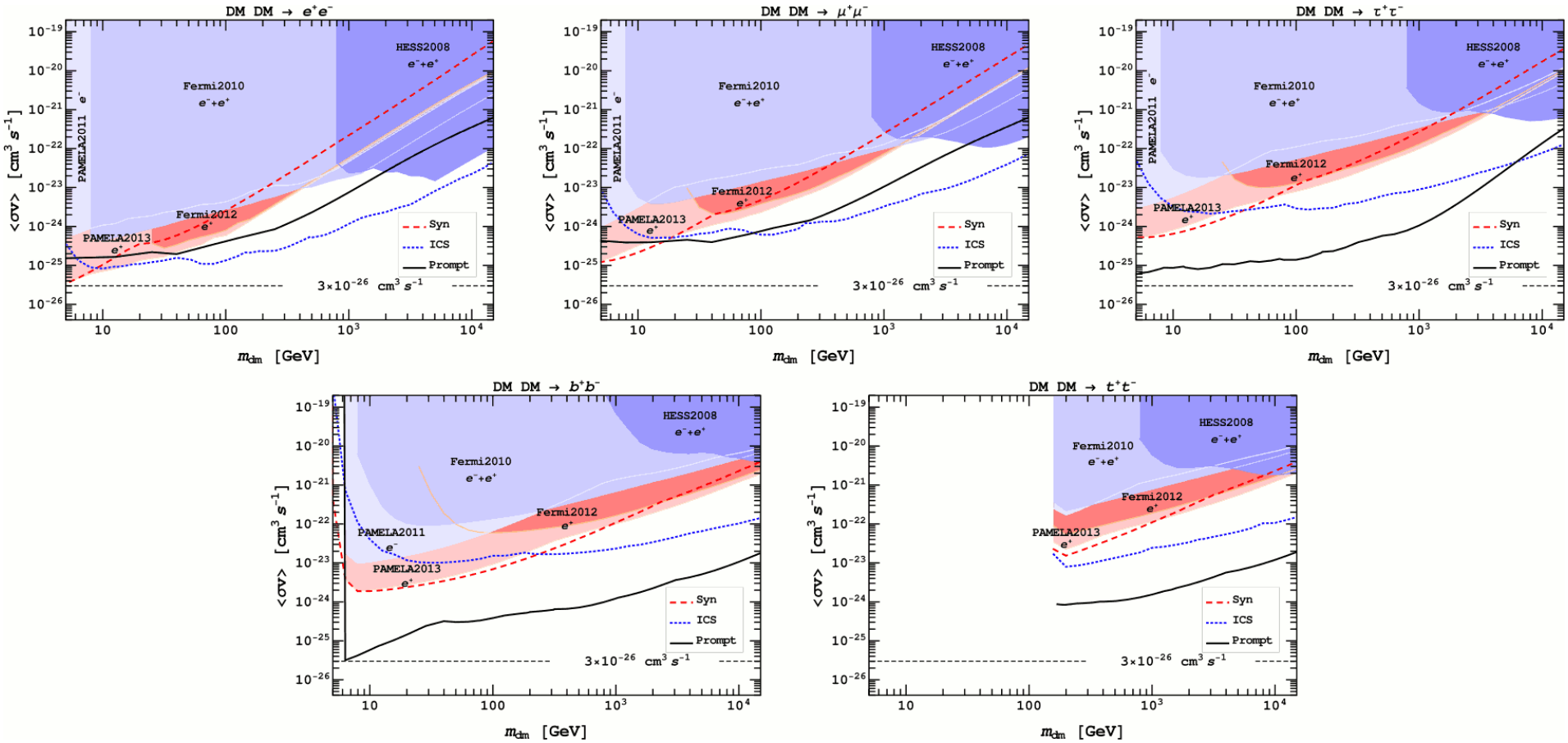


Adriani et al. (2009b)



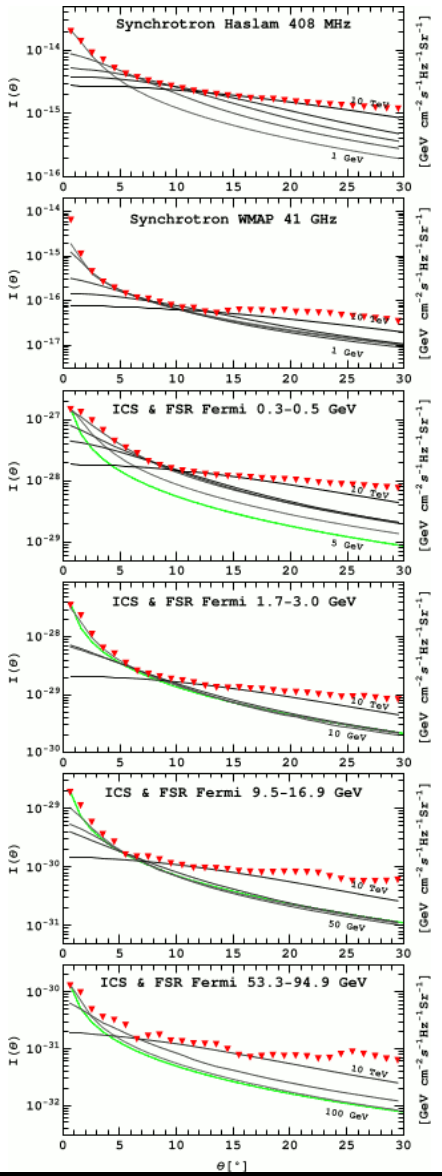
Weidenspointner et al. (2008)

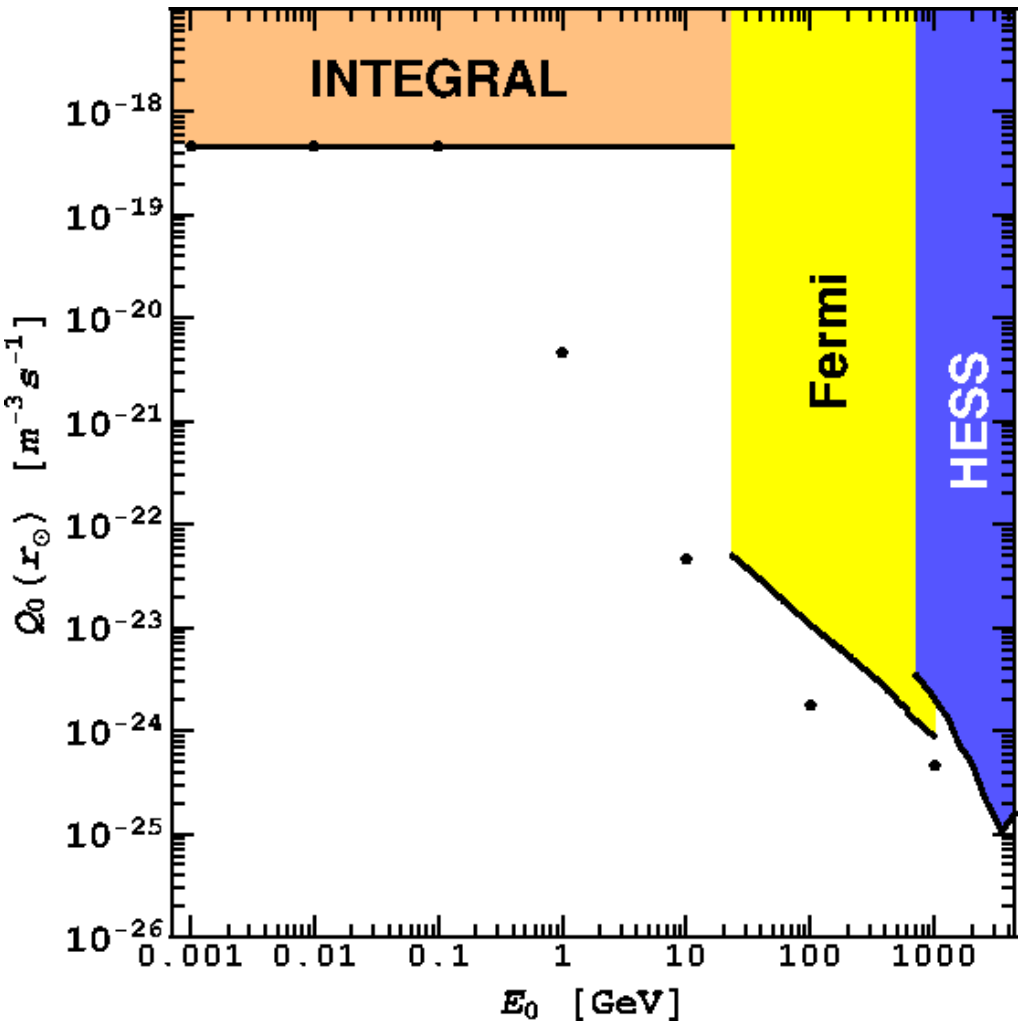
Have we detected dark matter?



Wechakama & Ascasibar (2014)

Have we detected something else?





Non-thermal pressure support

Equipartition

$$P_B \sim P_{CR} \sim P_v \sim \frac{P_{nt}}{3}$$

Magnetic field

$$P_B \propto B^2$$

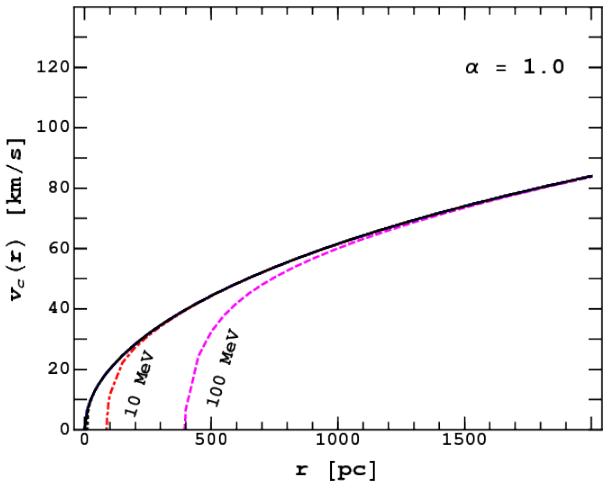
Cosmic rays

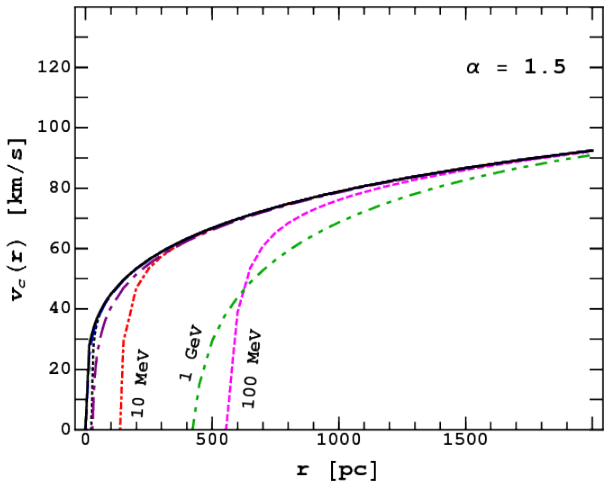
$$P_{CR} = \frac{E_0}{3} \int \frac{\mathrm{d}n_{CR}}{\mathrm{d}E} \frac{E^2 - E_0^2}{E} \, \mathrm{d}E$$

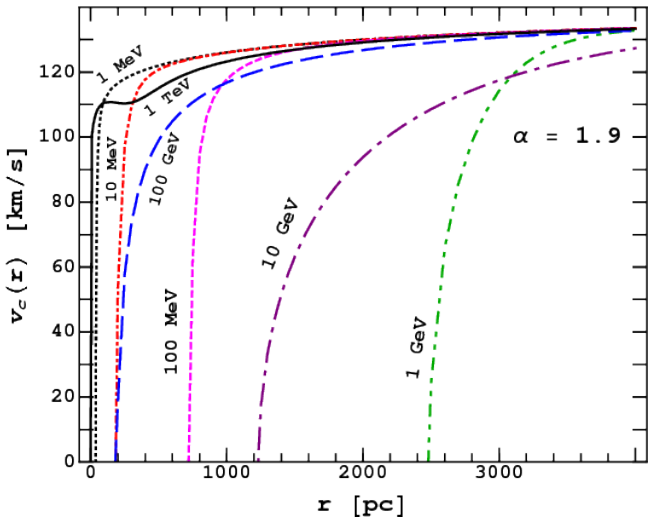
Turbulence

$$P_v \sim \rho \left\langle v^2 \right\rangle$$

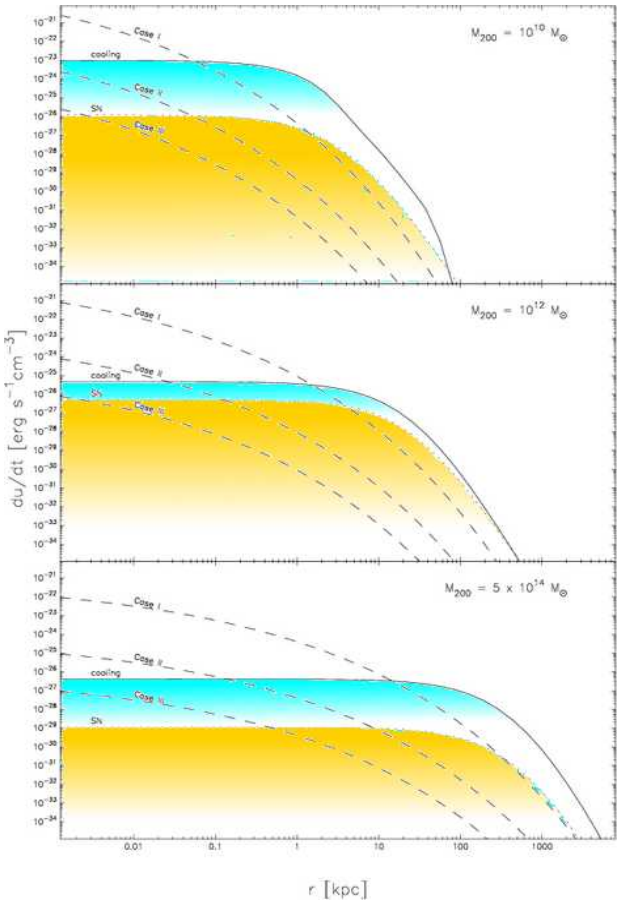
Non-thermal pressure support



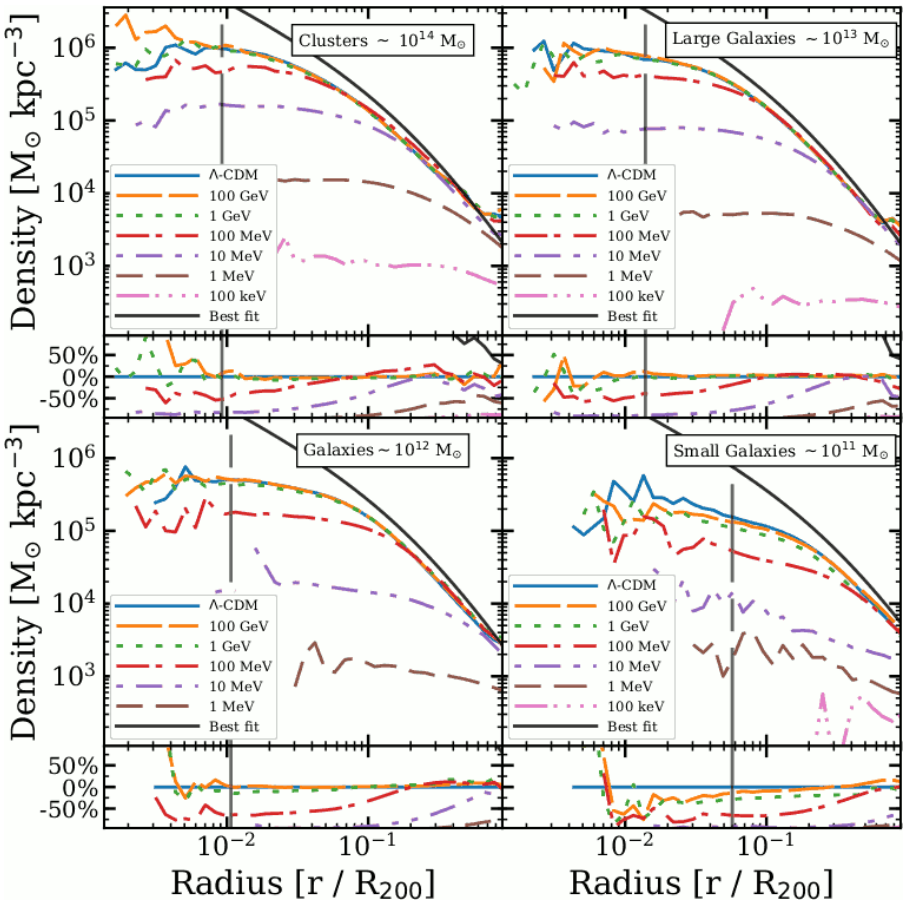




Heating and ionisation

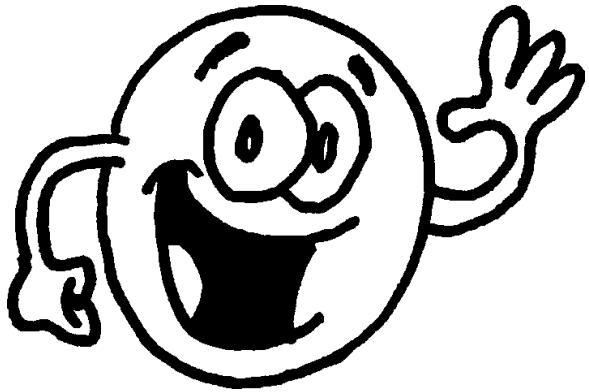


Ascasibar (2007)



Iwanus et al. (2019)

Conclusions



Noise

- Gamma rays
  - π^0 decay
  - ICS
- Radio continuum
  - synchrotron

Importance

- Pressure
- Energy
  - heating
  - ionization

Thank you!