

Title: The Astrophysics of Cosmic Rays

Speakers: Tova M. Yoast-Hull

Collection: PI-CITA Day 2019

Date: April 02, 2019 - 2:30 PM

URL: <http://pirsa.org/19020048>

The Astrophysics of Cosmic Rays

Dr. Tova Yoast-Hull

Canadian Institute for Theoretical Astrophysics
University of Toronto

2 Apr 2019



Copyright: Roberto Colombari

Cosmic Rays by Numbers

Cosmic Rays are
charged particles!

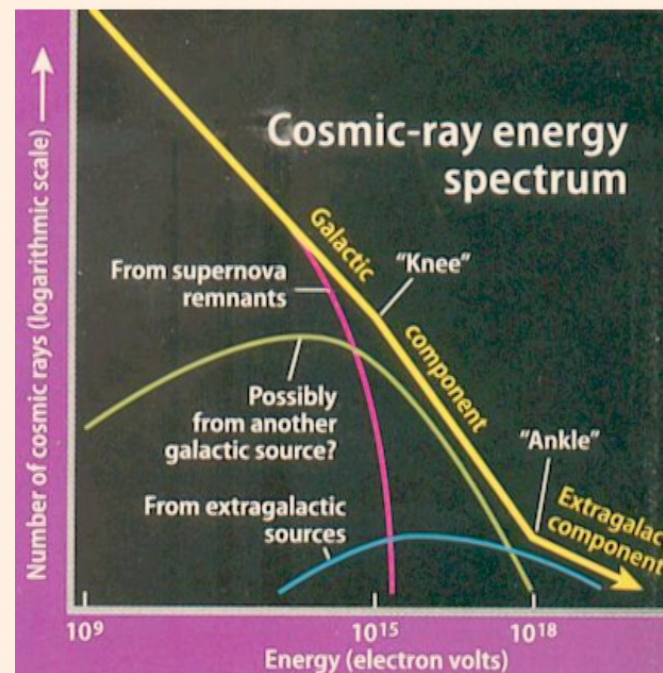
86% Protons

11% Helium Nuclei

1% Other Nuclei
(C, O, Si, Fe)

2% Electrons

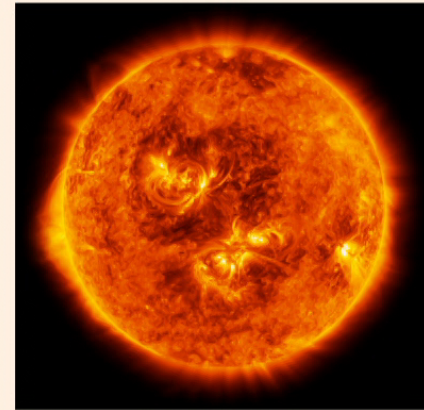
< 1% Positrons
(Anti-Electrons)
& Anti-Protons



$$U_{CR} \simeq U_B \simeq U_{rad} \simeq U_{turb} \simeq U_{gas}$$

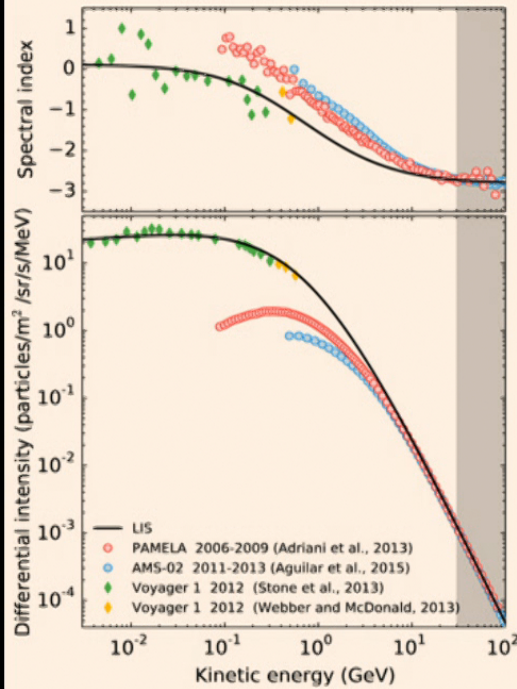
Low Energy Cosmic Rays

Solar!

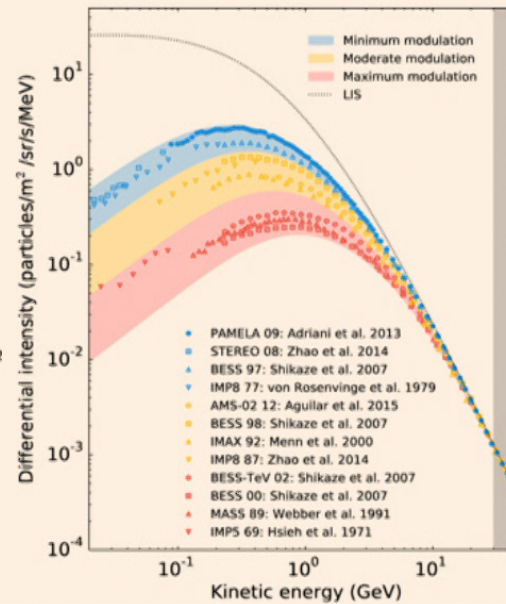


Energies: $10^7 - 10^{10}$ eV

Speeds: $0.18 - 0.993 c$



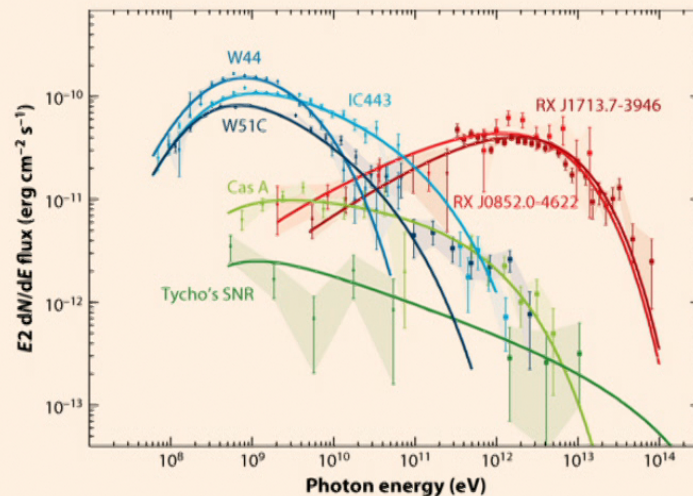
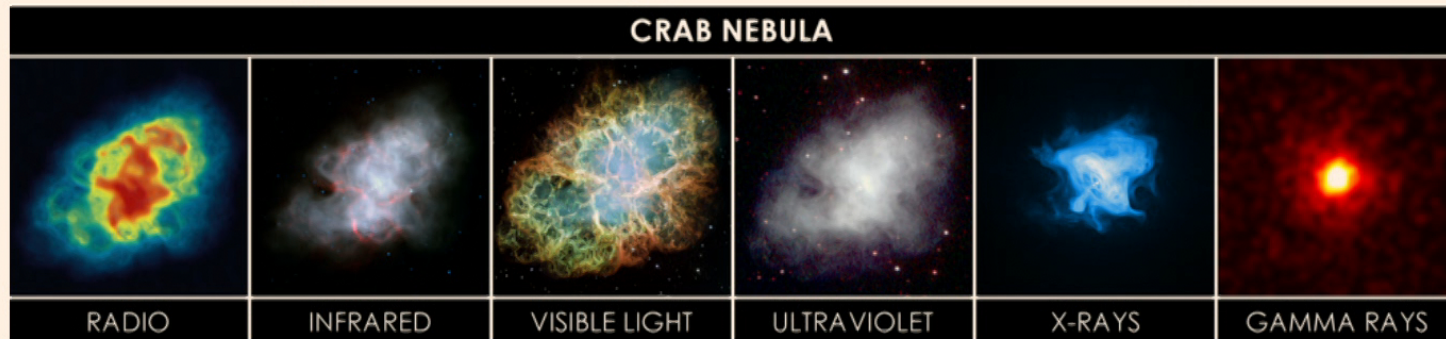
Vos & Potgieter 2015
ApJ, 815



Tova M. Yoast-Hull

Apr 2019, 3 / 27

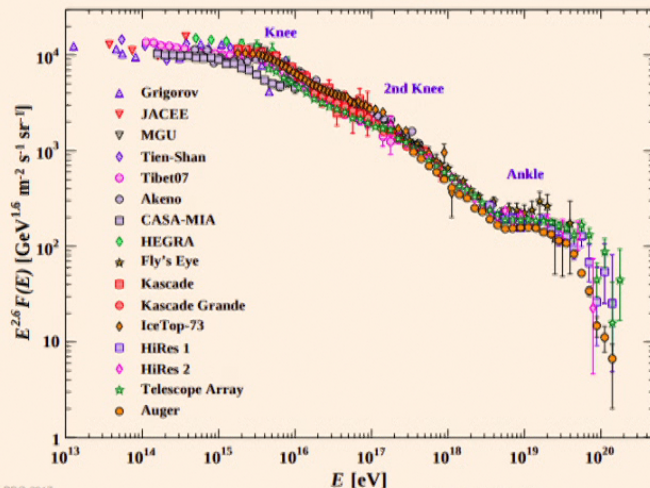
High Energy Cosmic Rays



Supernova Remnants
Pulsar Wind Nebulae
Novae

Energies: $10^8 - 10^{15}$ eV

Ultra High Energy Cosmic Rays

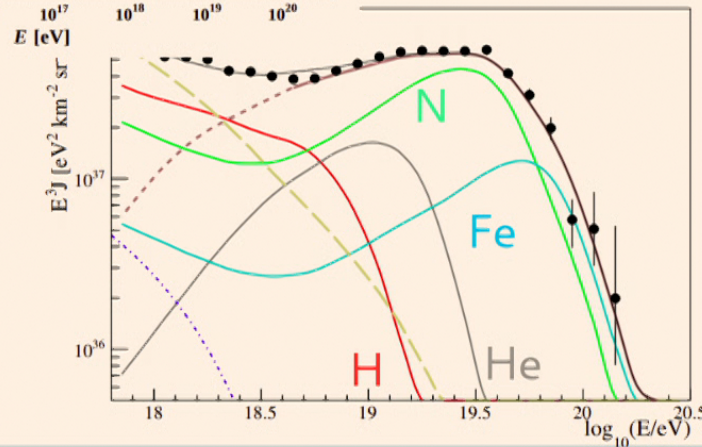


Highest
Energy CR:
 3×10^{20} eV



Active Galactic
Nuclei

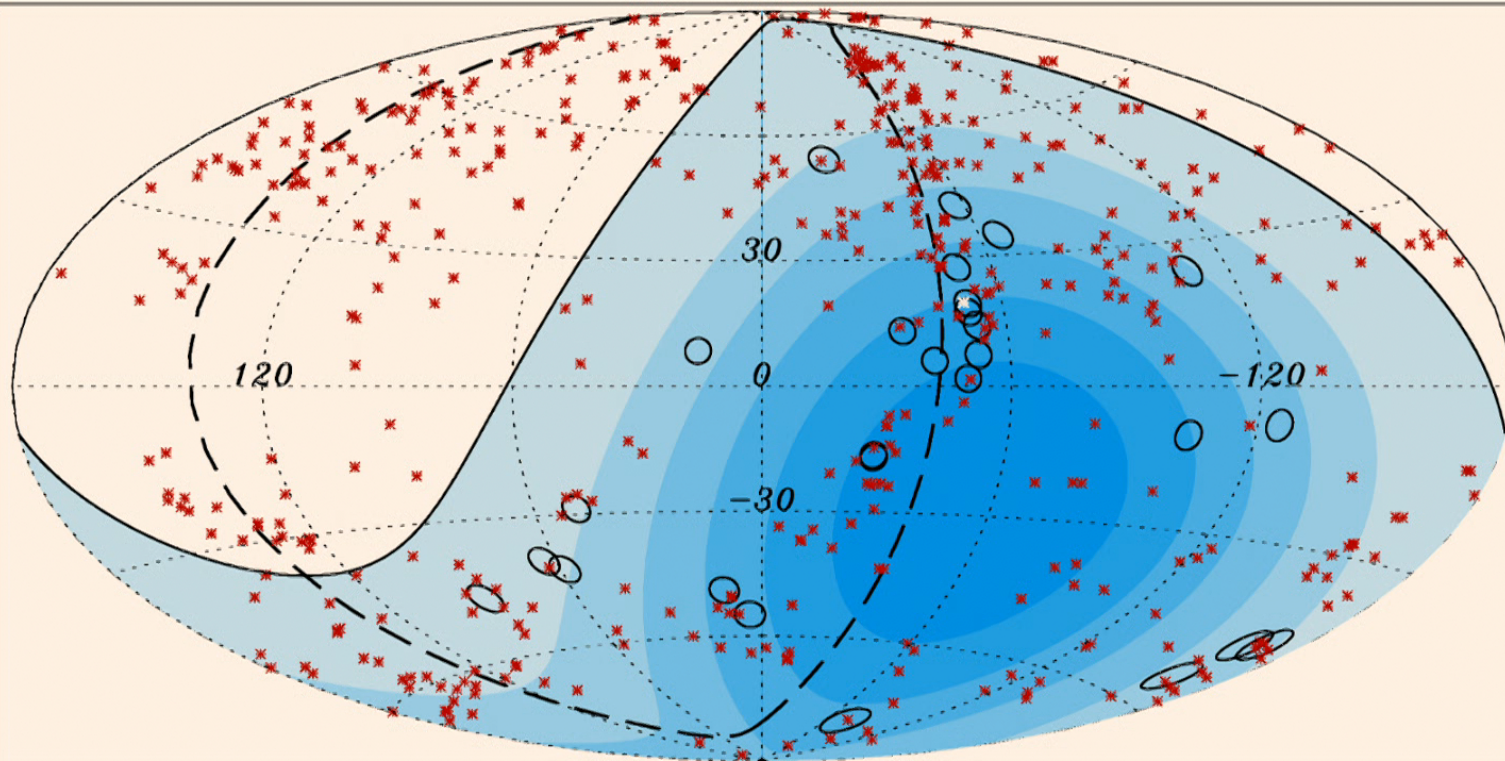
Energies: $10^{18} - 10^{20}$ eV



Tova M. Yoast-Hull

Apr 2019, 5 / 27

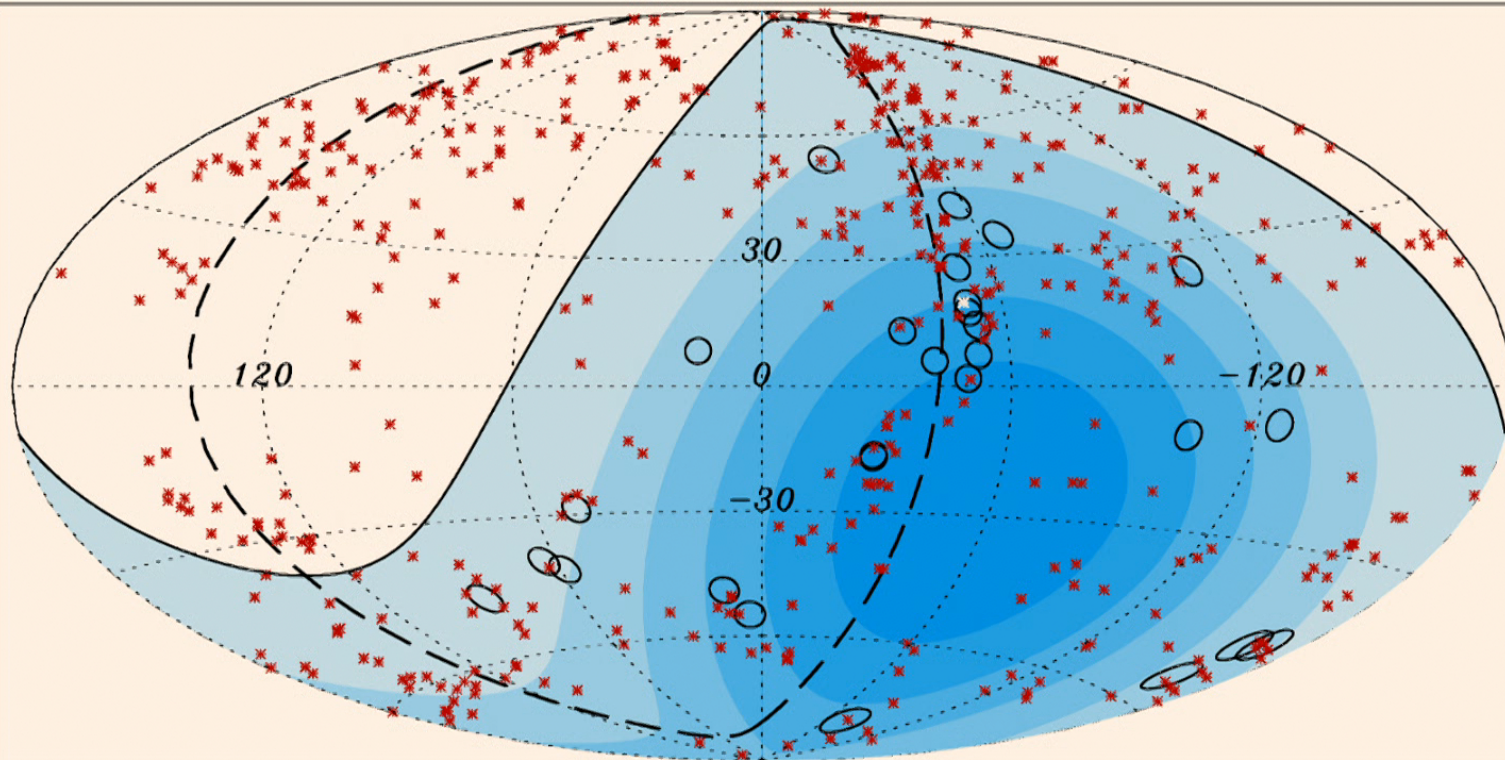
Ultra High Energy Cosmic Rays



Tova M. Yoast-Hull

Apr 2019, 6 / 27

Ultra High Energy Cosmic Rays

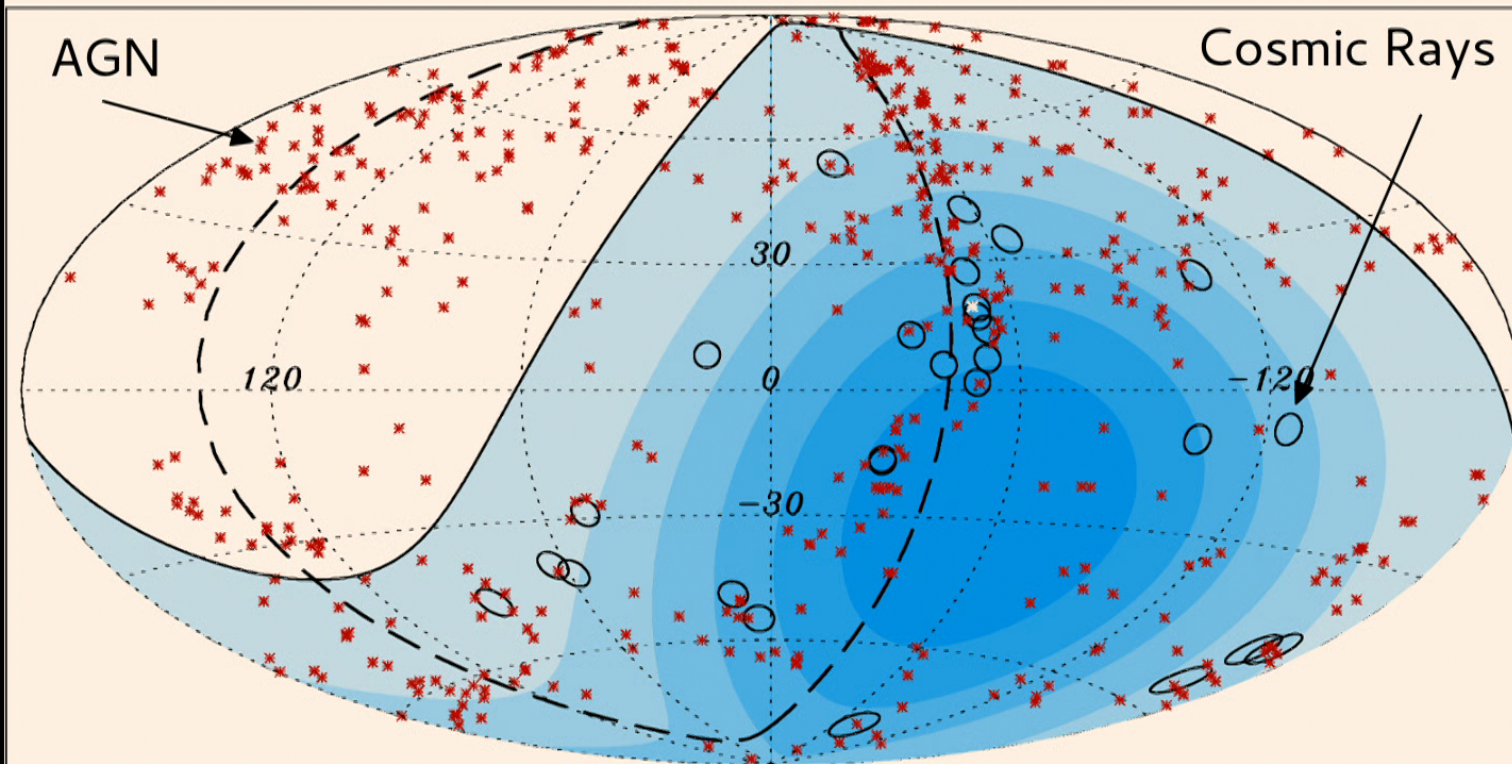


Sensitivity or Field of View

Tova M. Yoast-Hull

Apr 2019, 6 / 27

Ultra High Energy Cosmic Rays

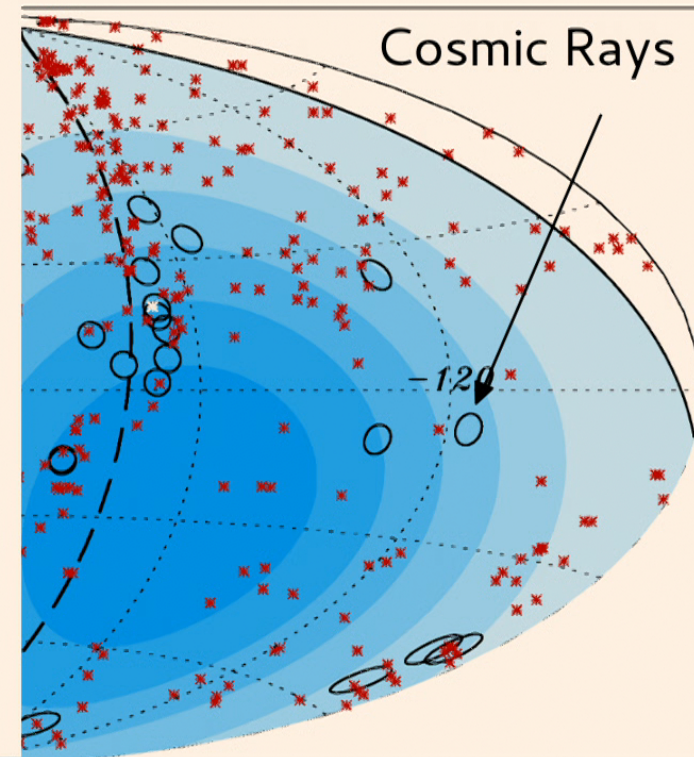
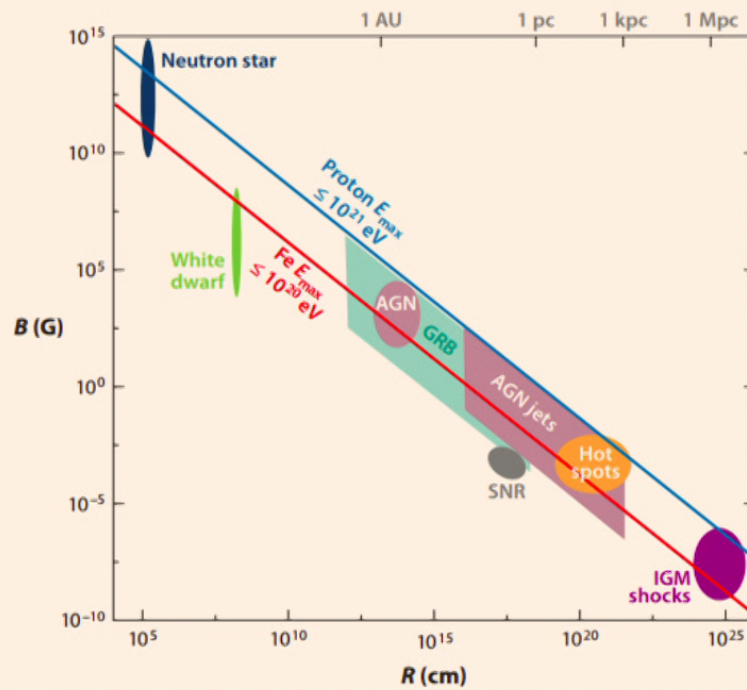


Sensitivity or Field of View

Tova M. Yoast-Hull

Apr 2019, 6 / 27

Ultra High Energy Cosmic Rays

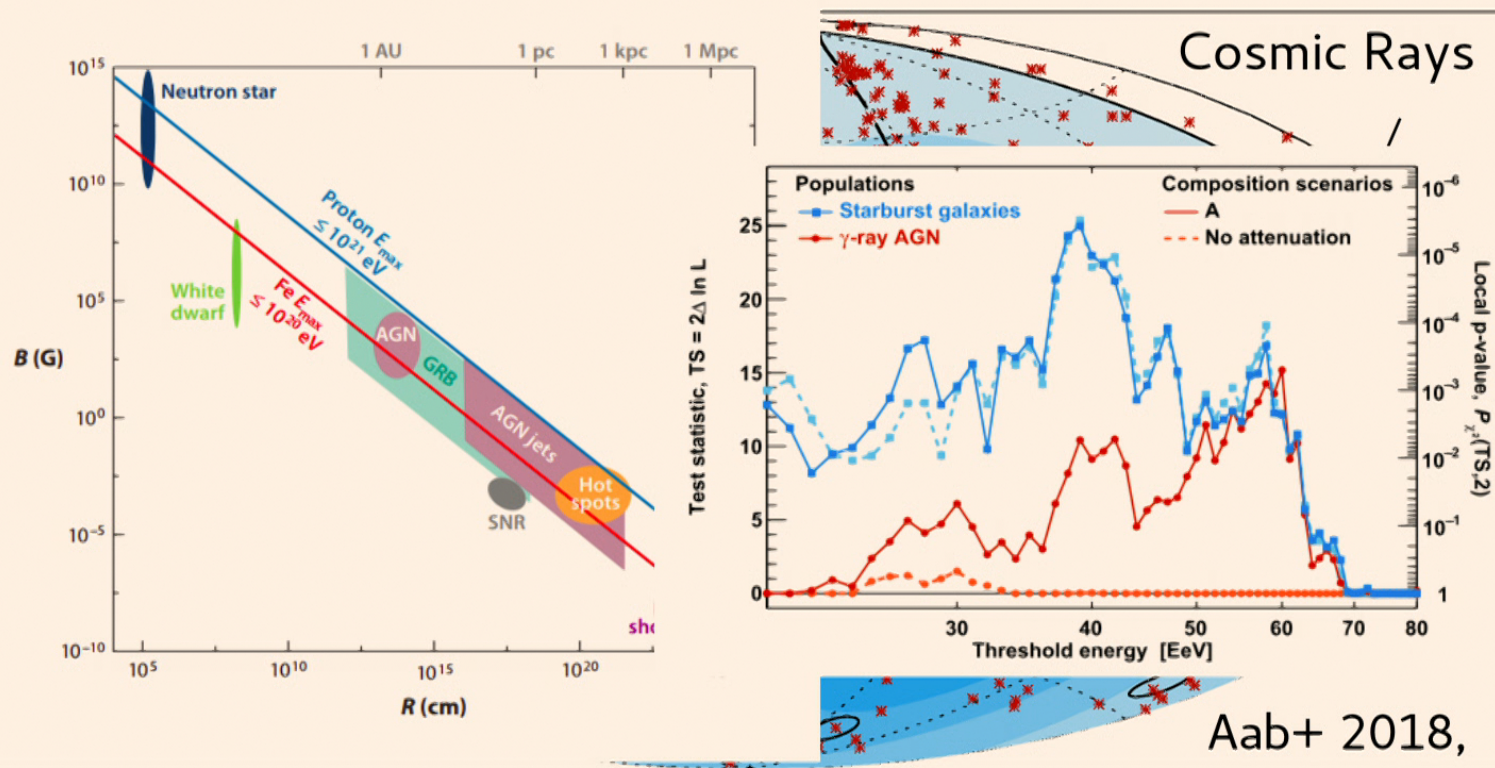


Sensitivity or Field of View

Tova M. Yoast-Hull

Apr 2019, 6 / 27

Ultra High Energy Cosmic Rays



Sensitivity or Field of View

Tova M. Yoast-Hull

Apr 2019, 6 / 27

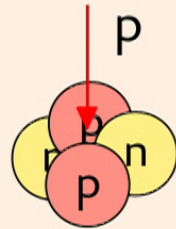
Aab+ 2018,
ApJL, 853

Cosmic Rays in the Atmosphere

Tova M. Yoast-Hull

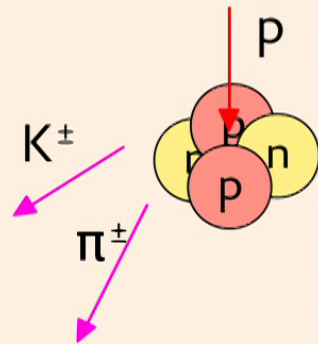
Apr 2019, 7 / 27

Cosmic Rays in the Atmosphere



Particles in Air Shower:

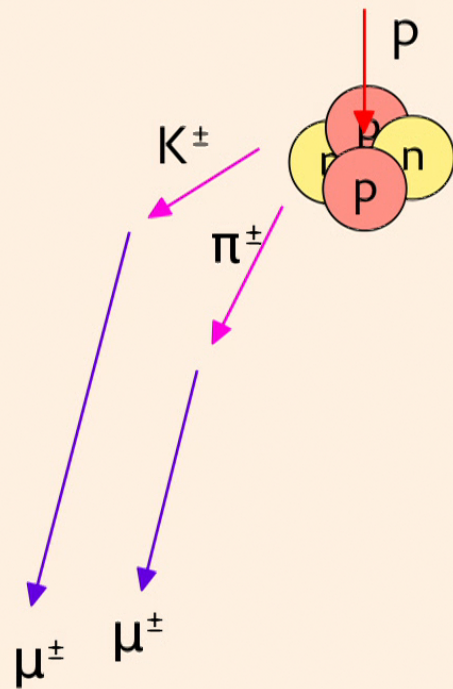
Cosmic Rays in the Atmosphere



Particles in Air Shower:

Pions & Kaons

Cosmic Rays in the Atmosphere

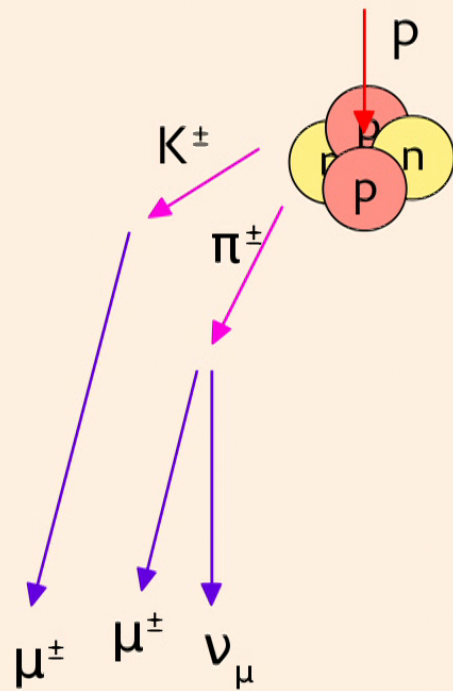


Particles in Air Shower:

Pions & Kaons

Muons

Cosmic Rays in the Atmosphere



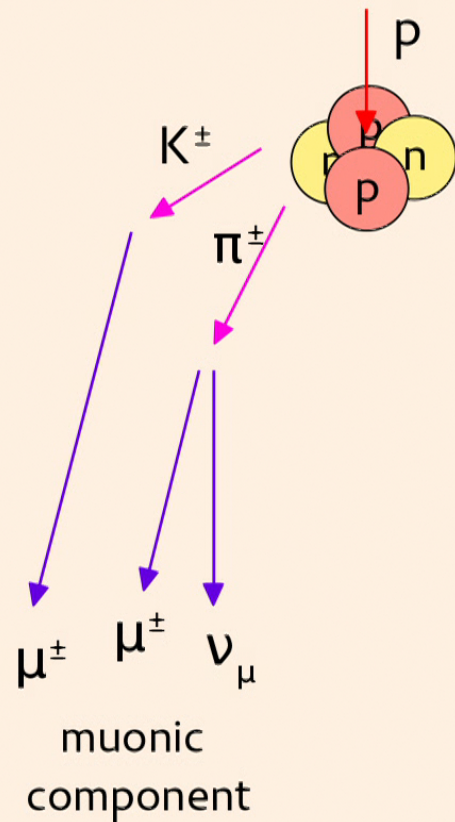
Particles in Air Shower:

Pions & Kaons

Muons

Neutrinos

Cosmic Rays in the Atmosphere



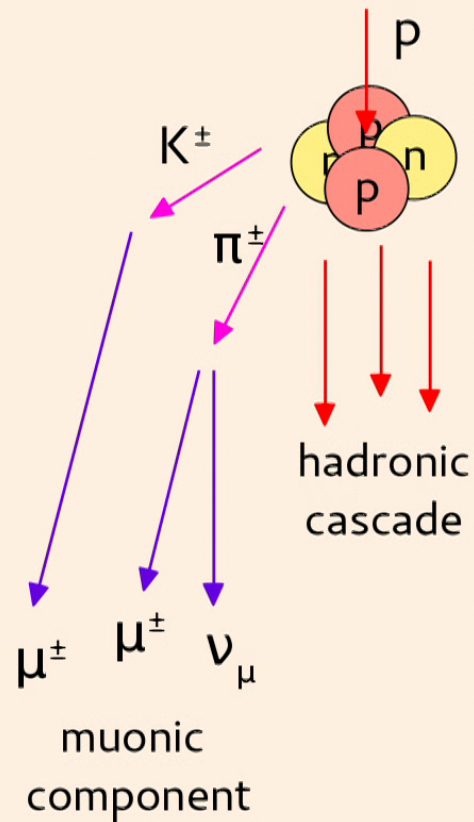
Particles in Air Shower:

Pions & Kaons

Muons

Neutrinos

Cosmic Rays in the Atmosphere



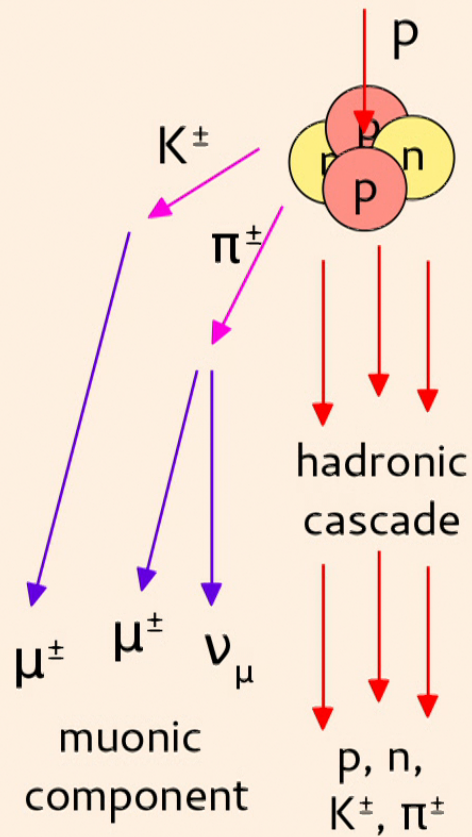
Particles in Air Shower:

Pions & Kaons

Muons

Neutrinos

Cosmic Rays in the Atmosphere



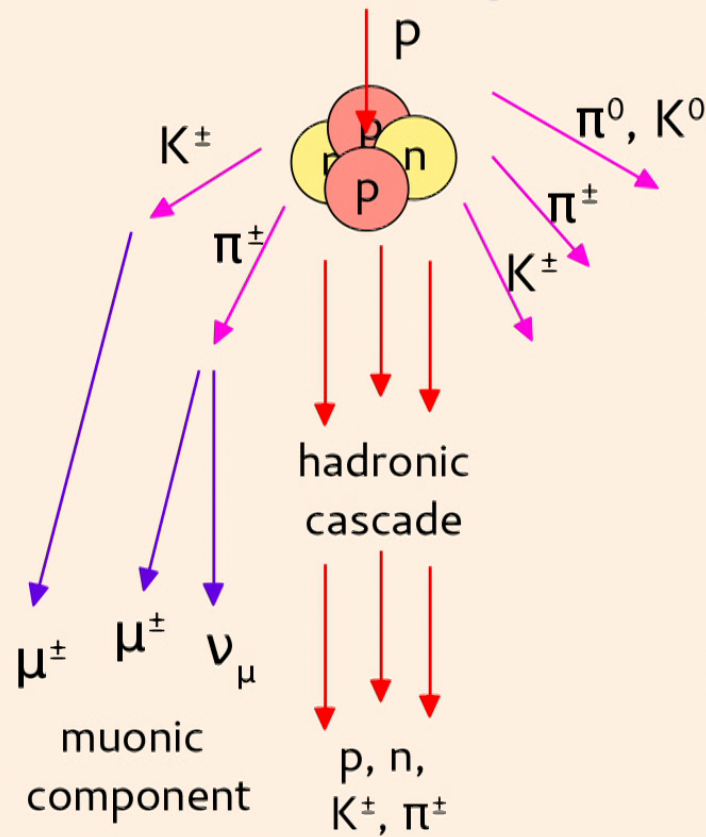
Particles in Air Shower:

Pions & Kaons

Muons

Neutrinos

Cosmic Rays in the Atmosphere



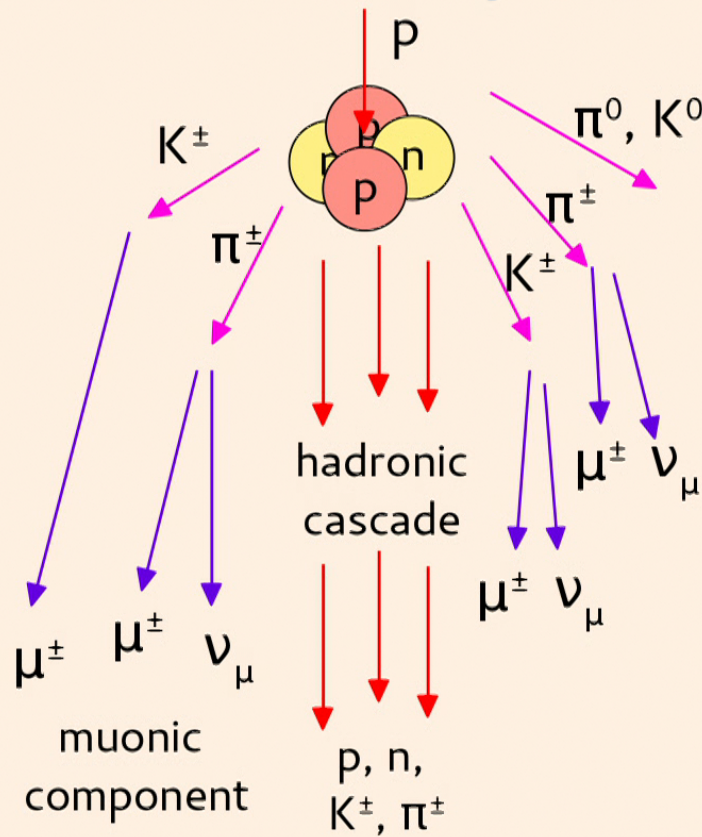
Particles in Air Shower:

Pions & Kaons

Muons

Neutrinos

Cosmic Rays in the Atmosphere



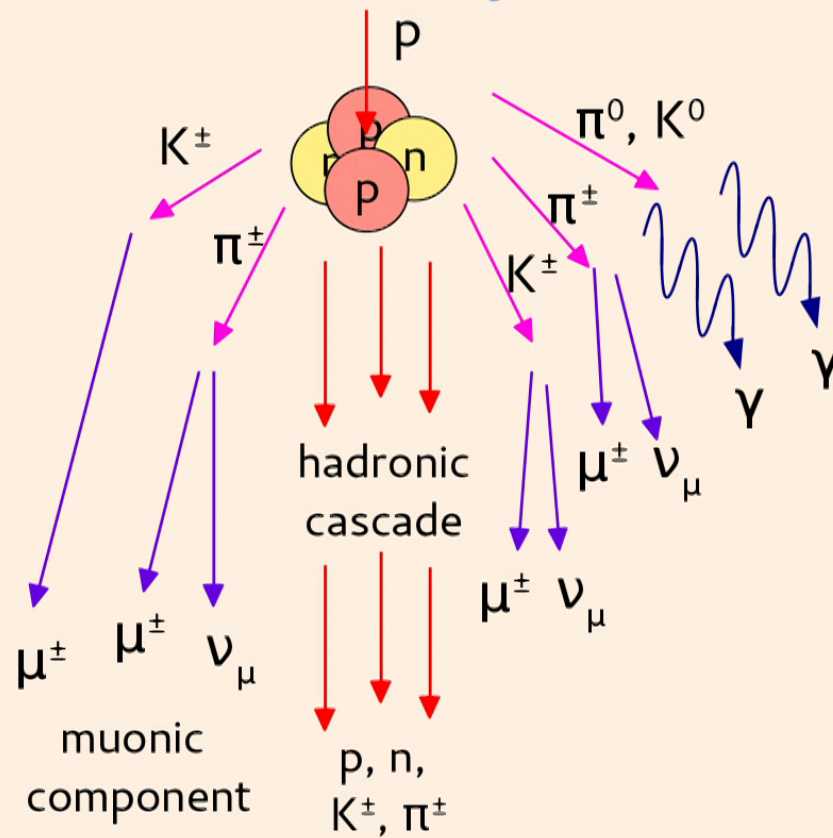
Particles in Air Shower:

Pions & Kaons

Muons

Neutrinos

Cosmic Rays in the Atmosphere



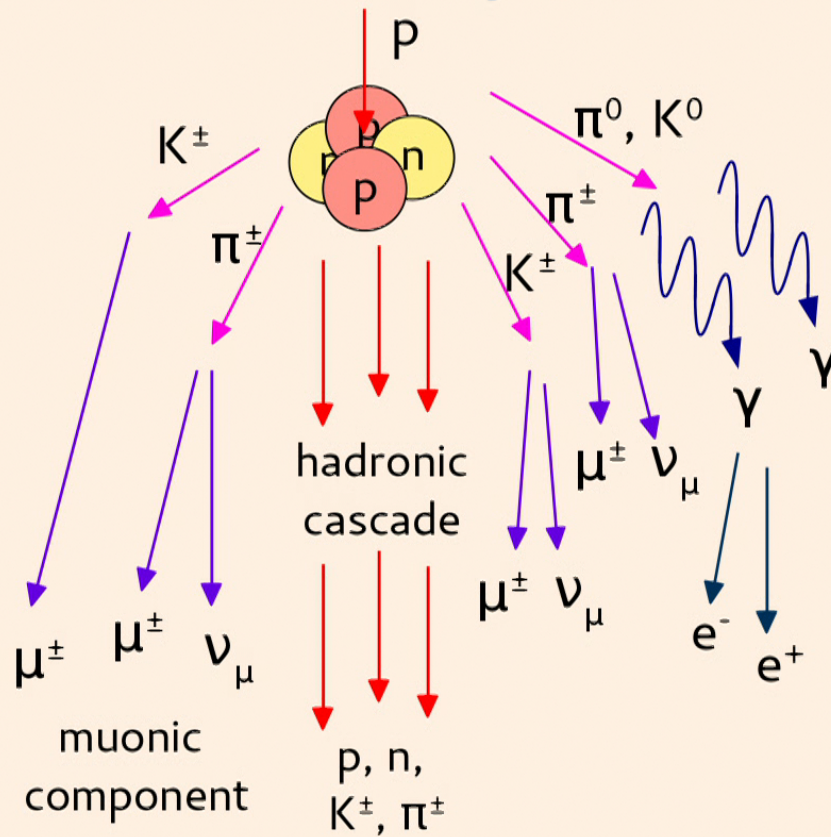
Particles in Air Shower:

Pions & Kaons

Muons

Neutrinos

Cosmic Rays in the Atmosphere



Particles in Air Shower:

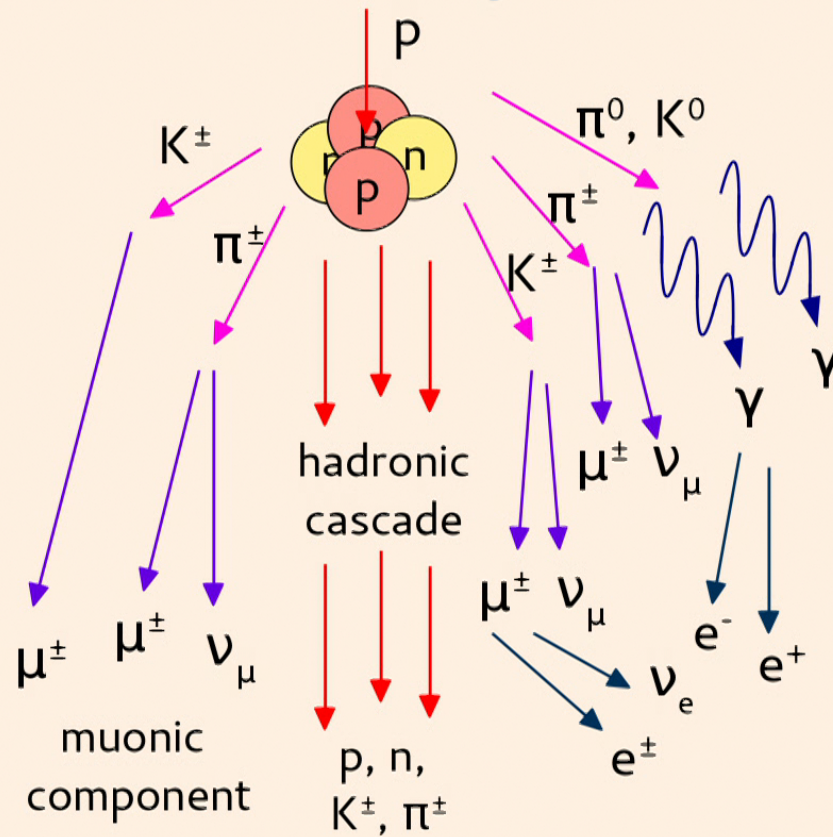
Pions & Kaons

Muons

Neutrinos

Electrons & Positrons

Cosmic Rays in the Atmosphere



Particles in Air Shower:

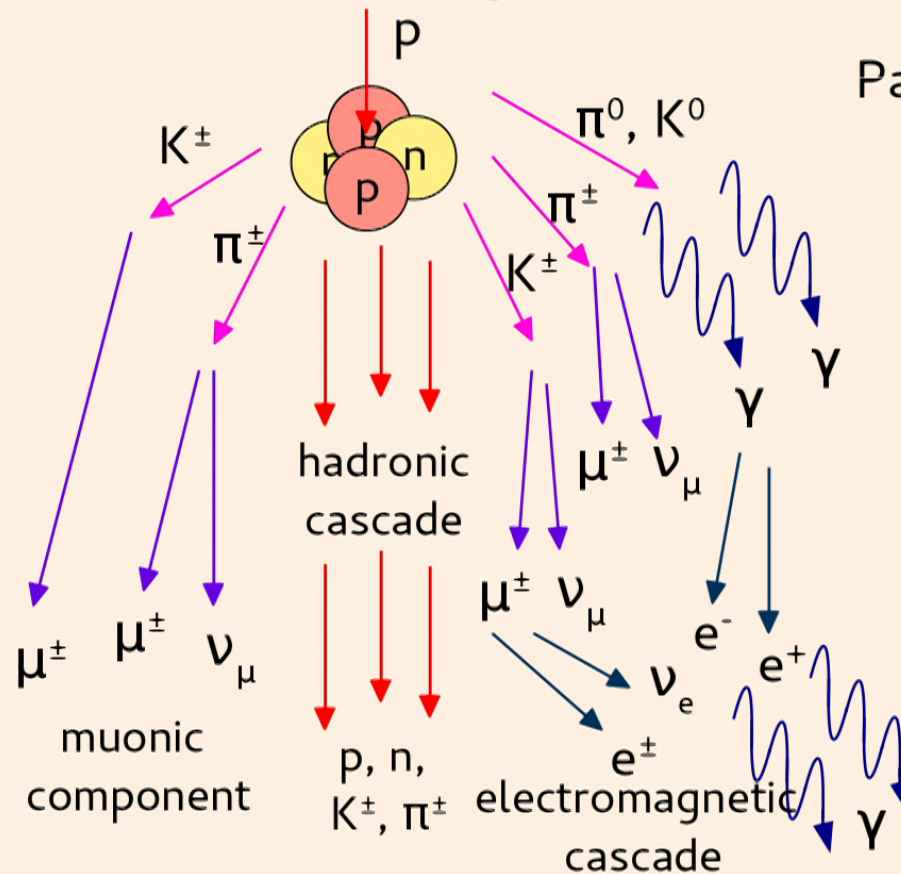
Pions & Kaons

Muons

Neutrinos

Electrons & Positrons

Cosmic Rays in the Atmosphere



Particles in Air Shower:

Pions & Kaons

Muons

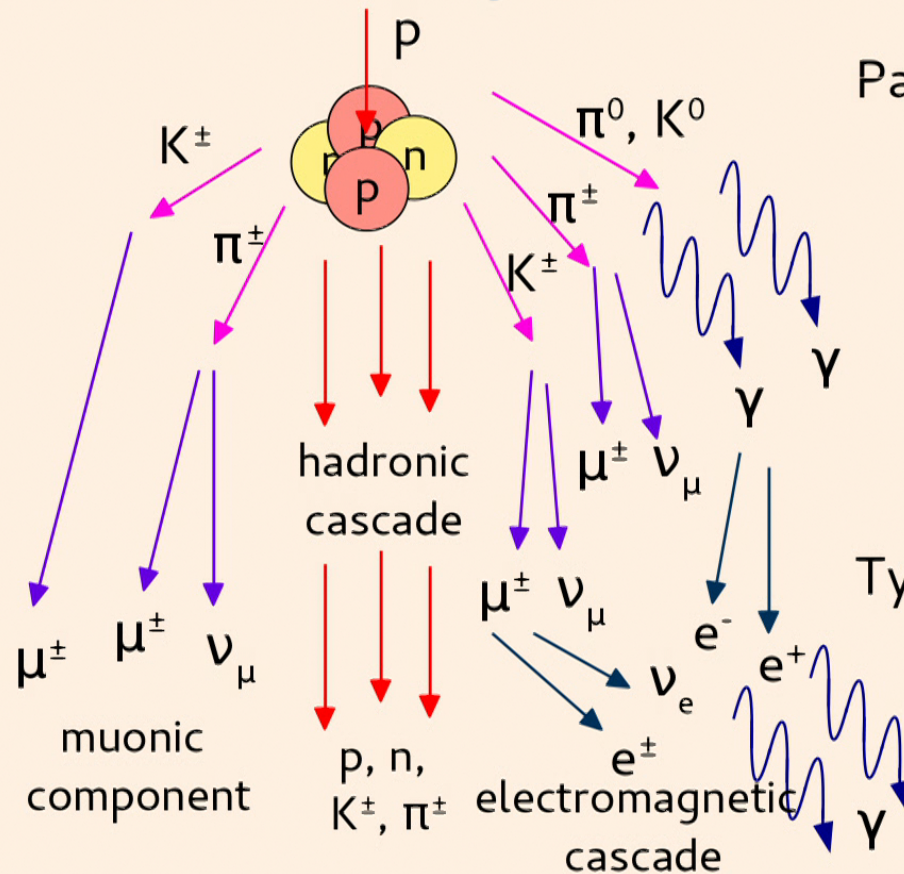
Neutrinos

Electrons & Positrons

Tova M. Yoast-Hull

Apr 2019, 7 / 27

Cosmic Rays in the Atmosphere



Particles in Air Shower:

Pions & Kaons

Muons

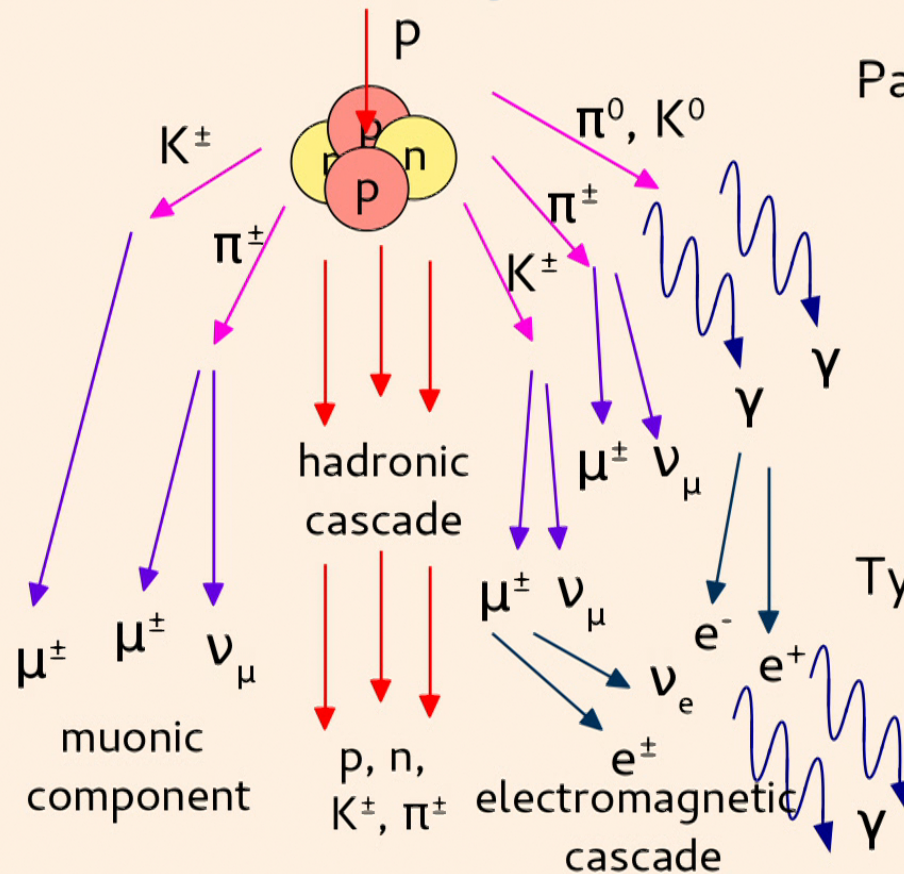
Neutrinos

Electrons & Positrons

Types of Radiation:

UV Fluorescence

Cosmic Rays in the Atmosphere



Particles in Air Shower:

Pions & Kaons

Muons

Neutrinos

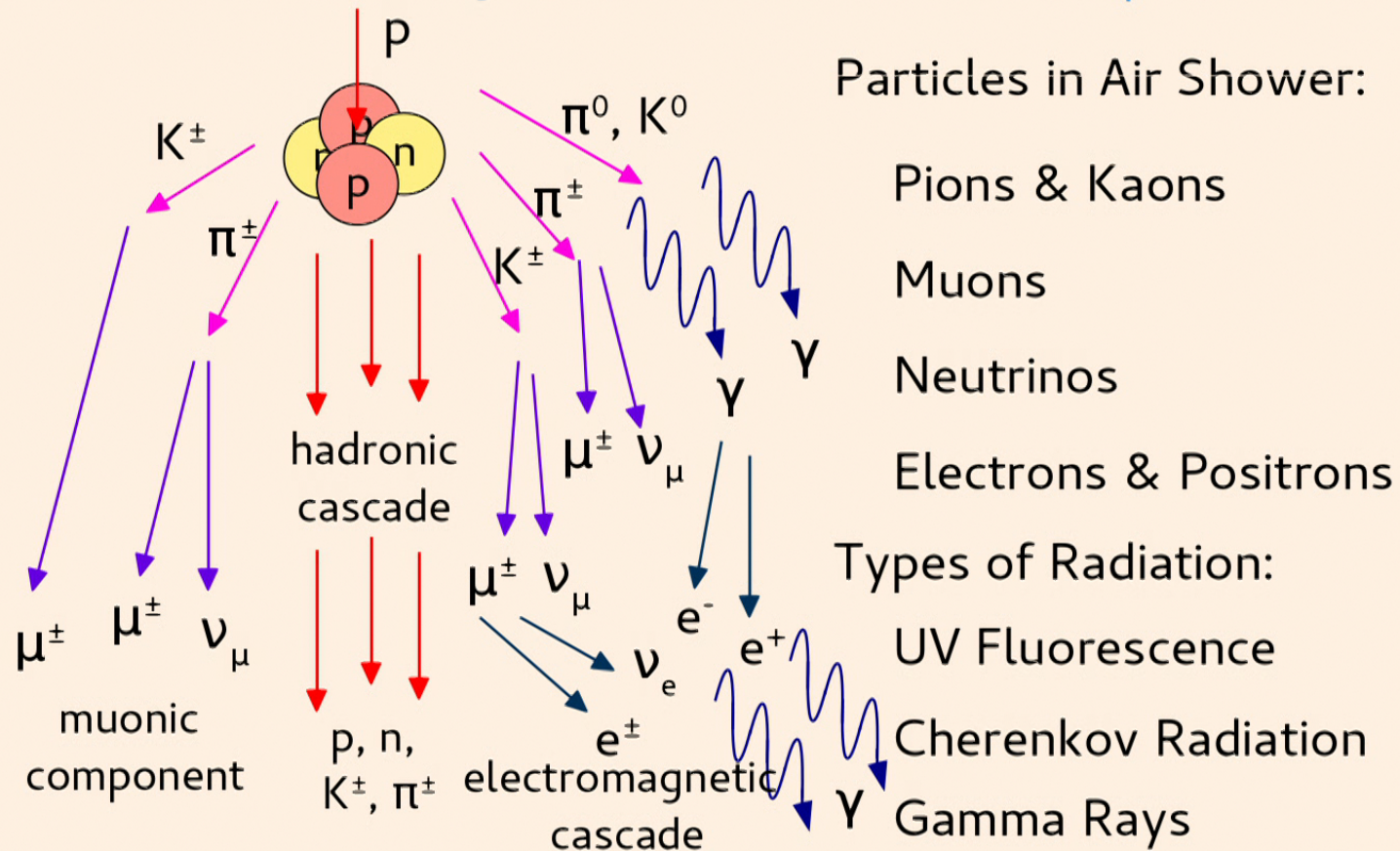
Electrons & Positrons

Types of Radiation:

UV Fluorescence

Cherenkov Radiation

Cosmic Rays in the Atmosphere



Tova M. Yoast-Hull

Apr 2019, 7 / 27

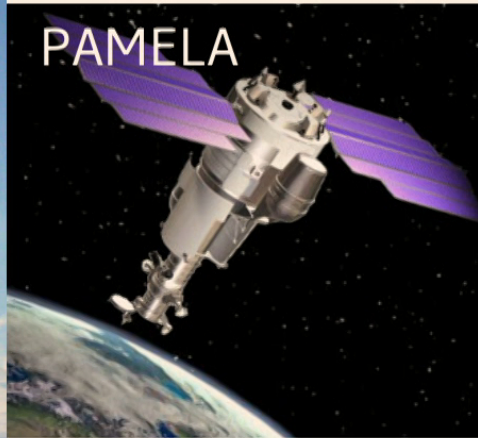
Detecting Cosmic Rays



Tova M. Yoast-Hull

Apr 2019, 8 / 27

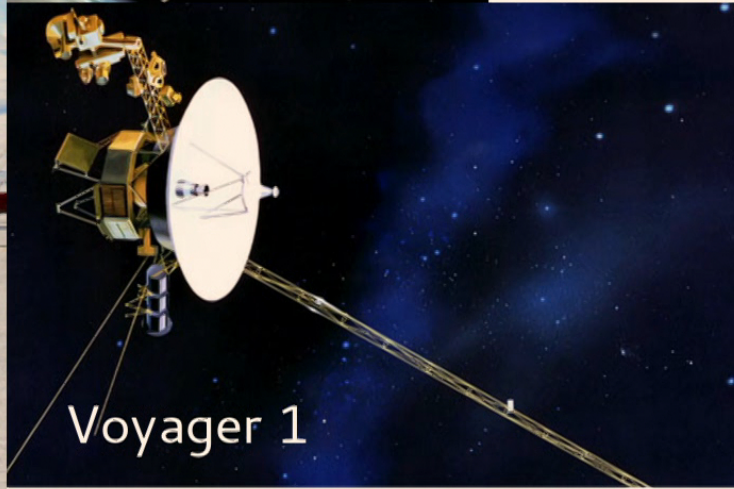
Detecting Cosmic Rays



Tova M. Yoast-Hull

Apr 2019, 8 / 27

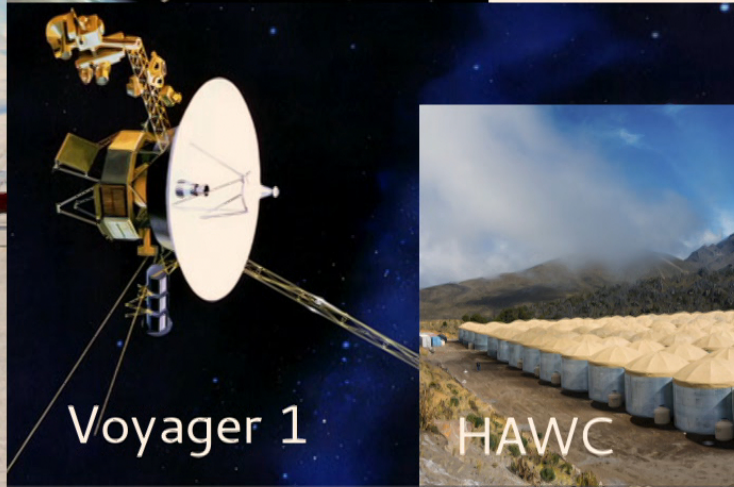
Detecting Cosmic Rays



Tova M. Yoast-Hull

Apr 2019, 8 / 27

Detecting Cosmic Rays



Tova M. Yoast-Hull

Apr 2019, 8 / 27

Detecting Cosmic Rays



Tova M. Yoast-Hull

Apr 2019, 8 / 27

Detecting Cosmic Rays

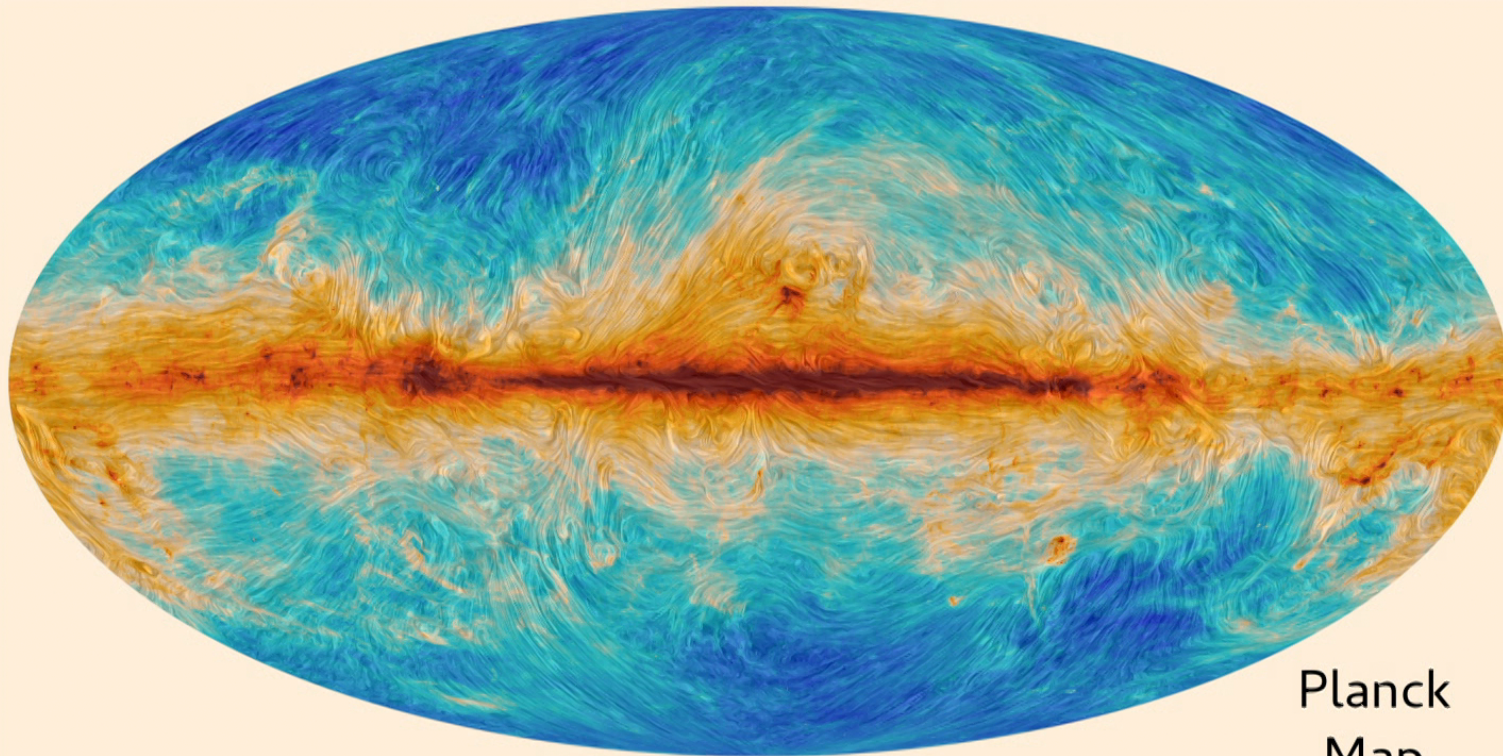


Tova M. Yoast-Hull

Apr 2019, 8 / 27

Galactic Magnetic Fields

Cosmic Rays are isotropic to one part in 1000!



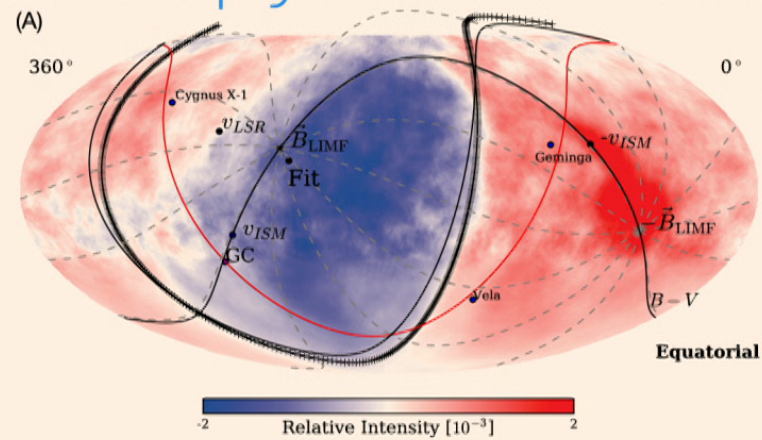
Planck
Map

Tova M. Yoast-Hull

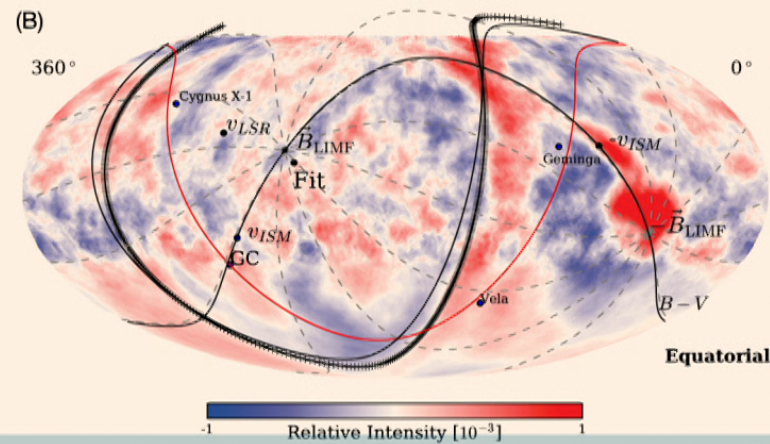
Apr 2019, 9 / 27

CR Anisotropy: HAWC-IceCube

Large
Scale



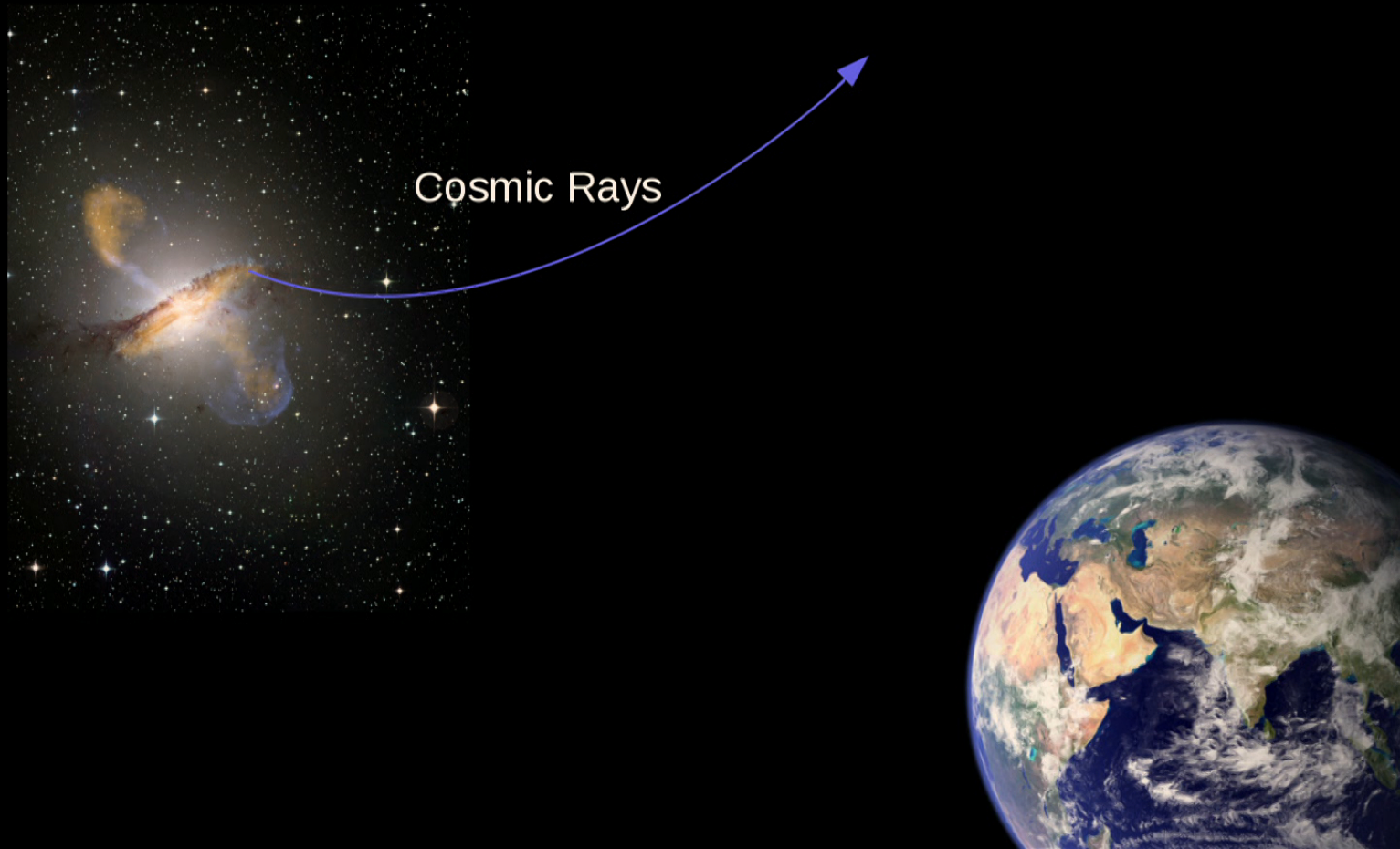
Small
Scale



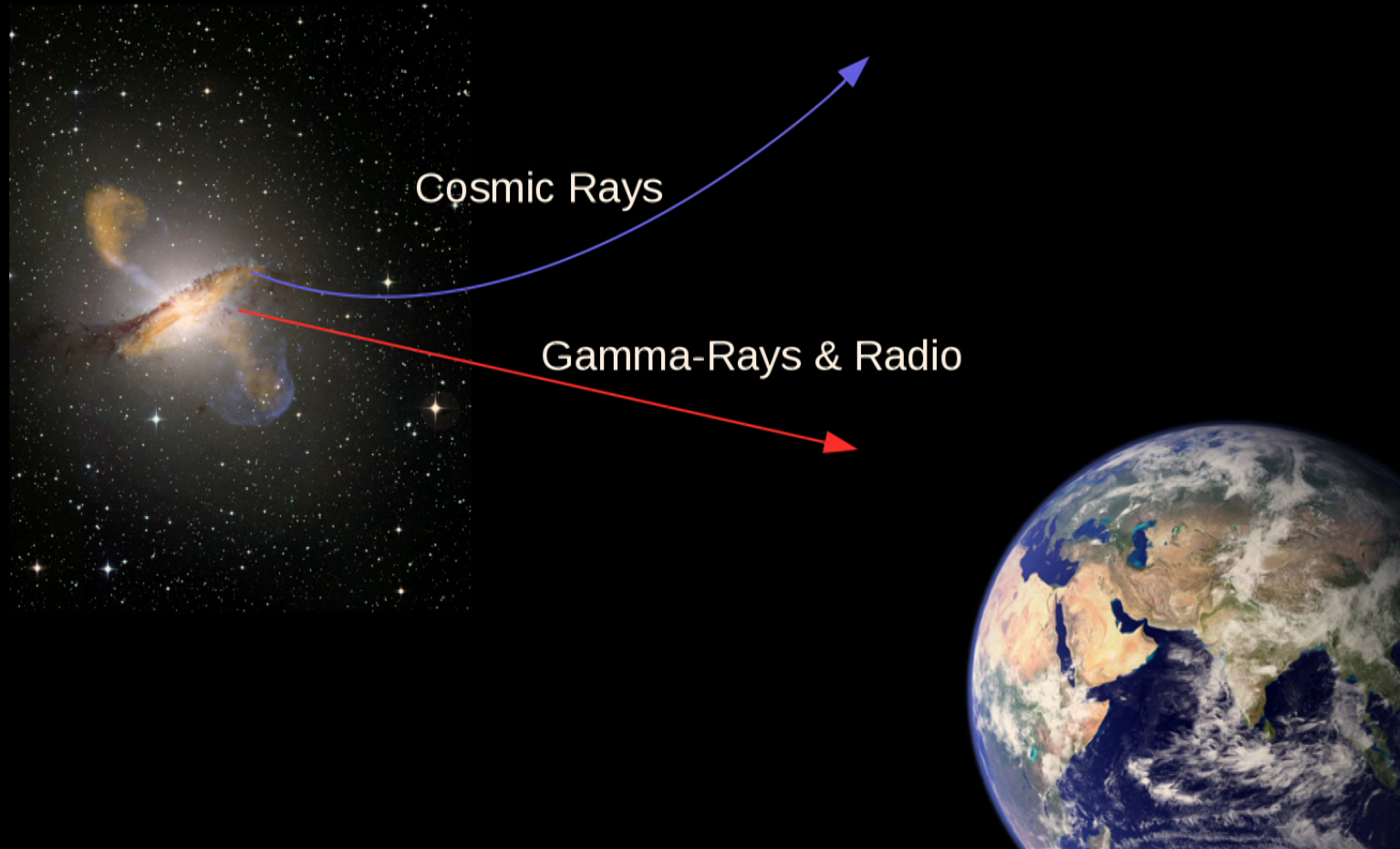
Tova M. Yoast-Hull

Apr 2019, 10 / 27

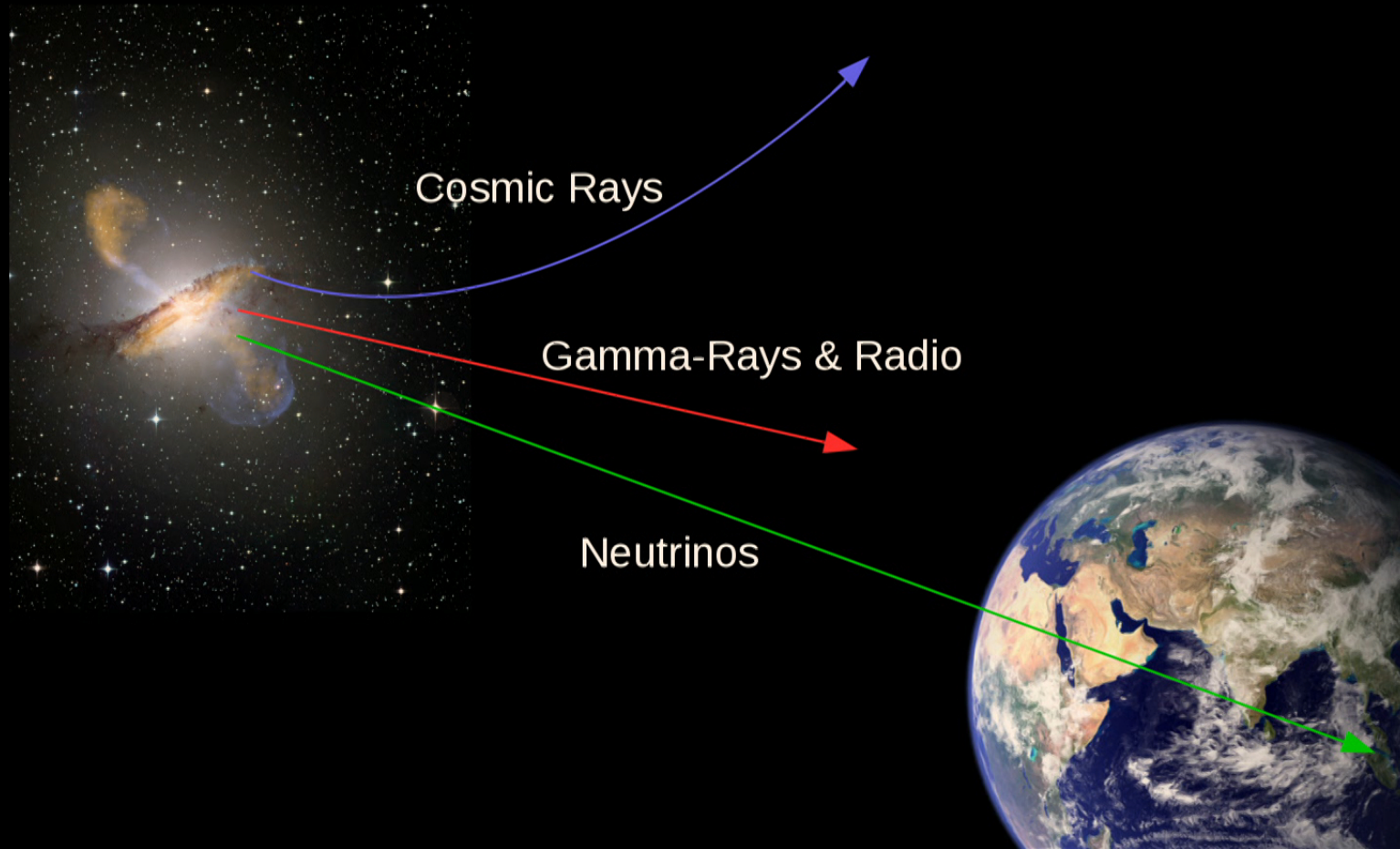
From Cosmic Ray Sources to Earth



From Cosmic Ray Sources to Earth



From Cosmic Ray Sources to Earth



Cosmic Ray Interactions

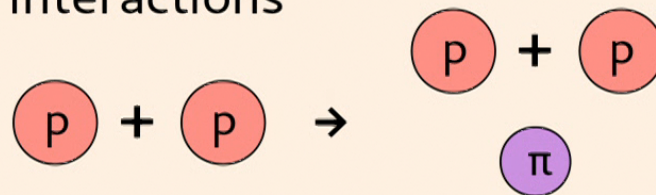
Proton-Proton Interactions

Tova M. Yoast-Hull

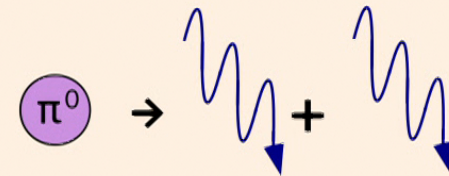
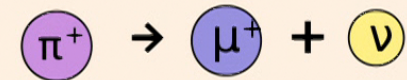
Apr 2019, 12 / 27

Cosmic Ray Interactions

Proton-Proton
Interactions

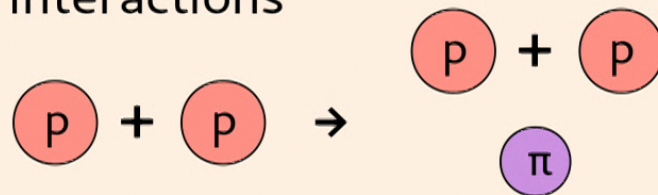


Pion Decay



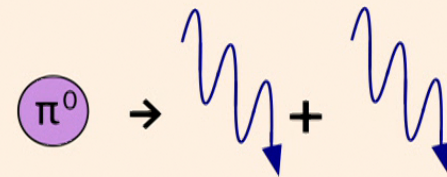
Cosmic Ray Interactions

Proton-Proton
Interactions



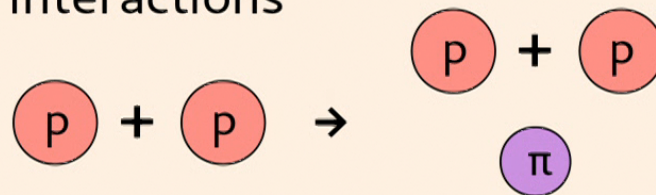
Electron-Nucleus
Interactions

Pion Decay

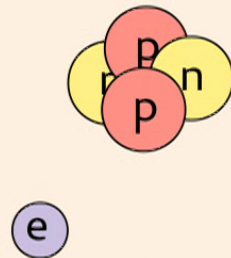


Cosmic Ray Interactions

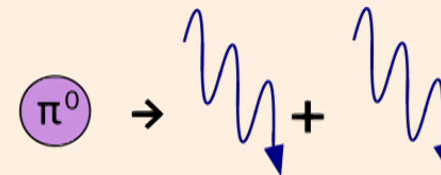
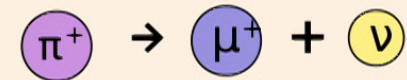
Proton-Proton
Interactions



Electron-Nucleus
Interactions

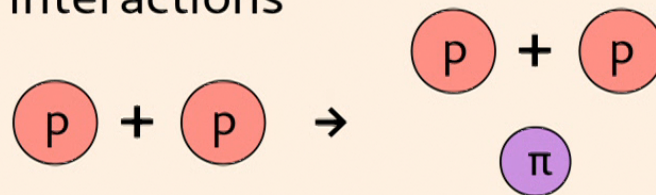


Pion Decay

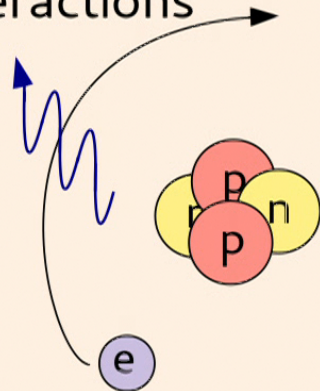


Cosmic Ray Interactions

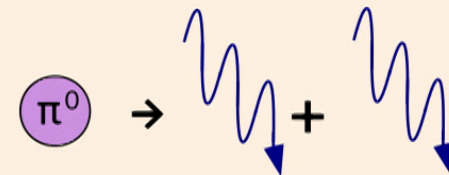
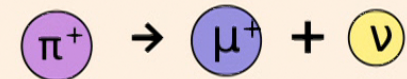
Proton-Proton
Interactions



Electron-Nucleus
Interactions

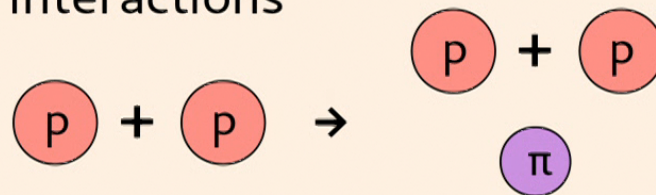


Pion Decay

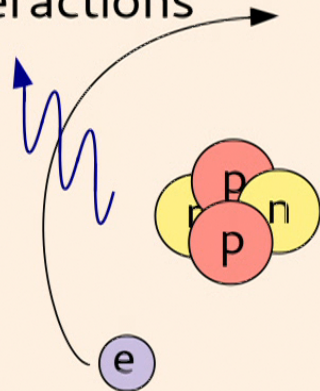


Cosmic Ray Interactions

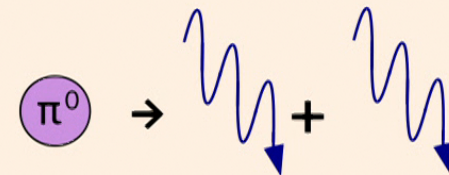
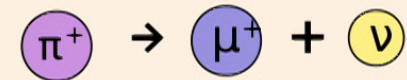
Proton-Proton Interactions



Electron-Nucleus Interactions



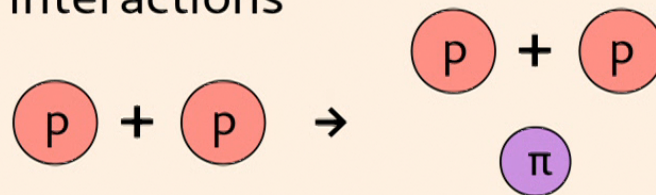
Pion Decay



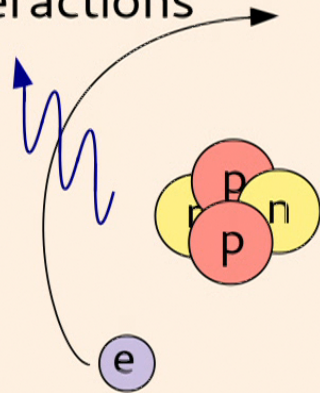
Electron-Photon Interactions

Cosmic Ray Interactions

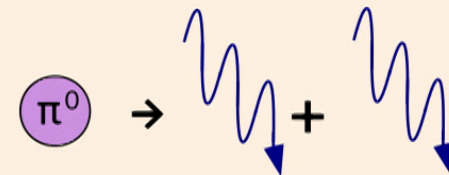
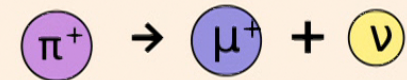
Proton-Proton Interactions



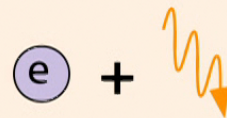
Electron-Nucleus Interactions



Pion Decay

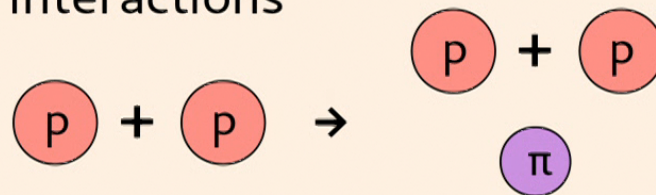


Electron-Photon Interactions

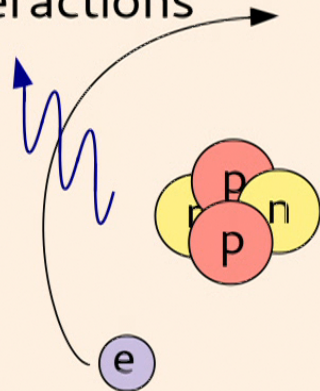


Cosmic Ray Interactions

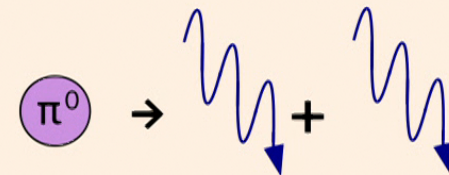
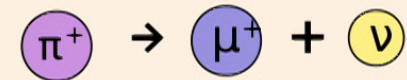
Proton-Proton Interactions



Electron-Nucleus Interactions



Pion Decay

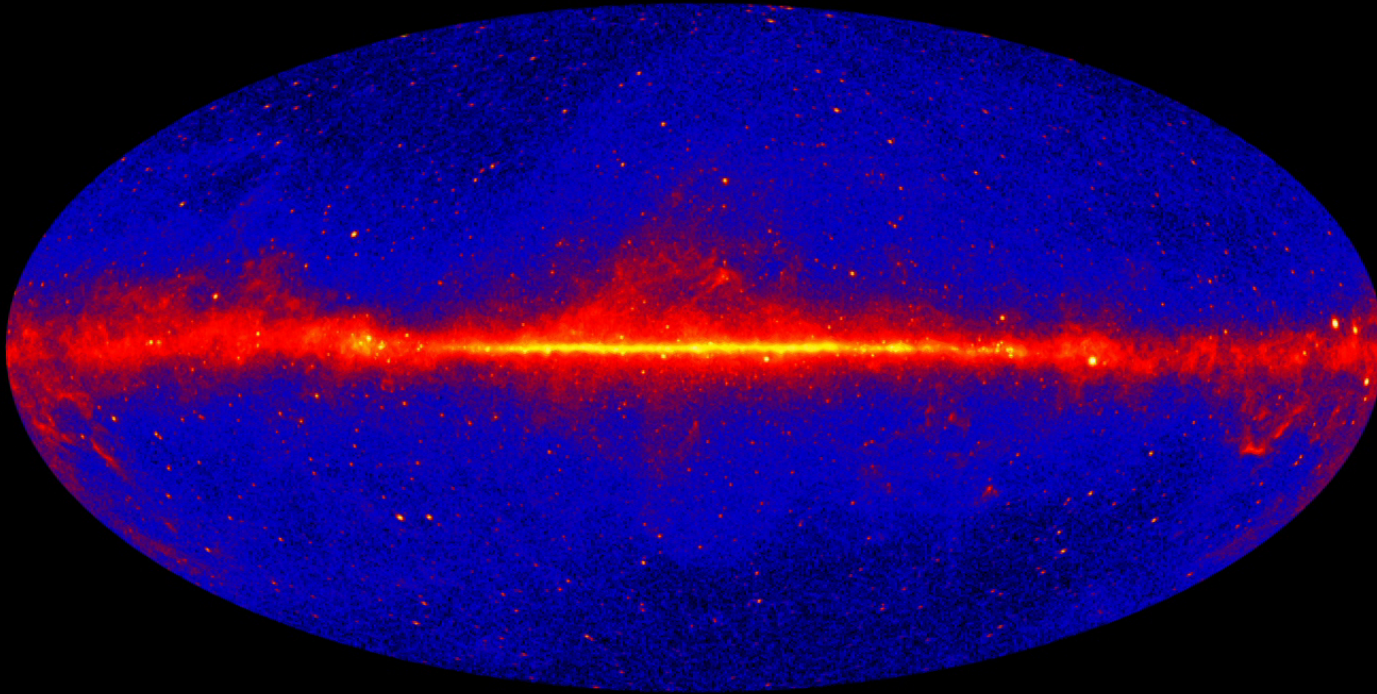


Electron-Photon Interactions



The Milky Way in Gamma Rays

Fermi 9 Year Map



Questions of Specific Interest

- How can we better study ***cosmic ray*** populations in other galaxies?

Questions of Specific Interest

- How can we better study ***cosmic ray*** populations in other galaxies?
 - What can gamma-ray and neutrino observations tell us?

Questions of Specific Interest

- How can we better study **cosmic ray** populations in other galaxies?
 - What can gamma-ray and neutrino observations tell us?
- How is energy distributed among **cosmic rays**, magnetic fields, thermal gas, and radiation in other galaxies?

Questions of Specific Interest

- How can we better study **cosmic ray** populations in other galaxies?
 - What can gamma-ray and neutrino observations tell us?
- How is energy distributed among **cosmic rays**, magnetic fields, thermal gas, and radiation in other galaxies?
 - In the Milky Way, energy is evenly distributed.

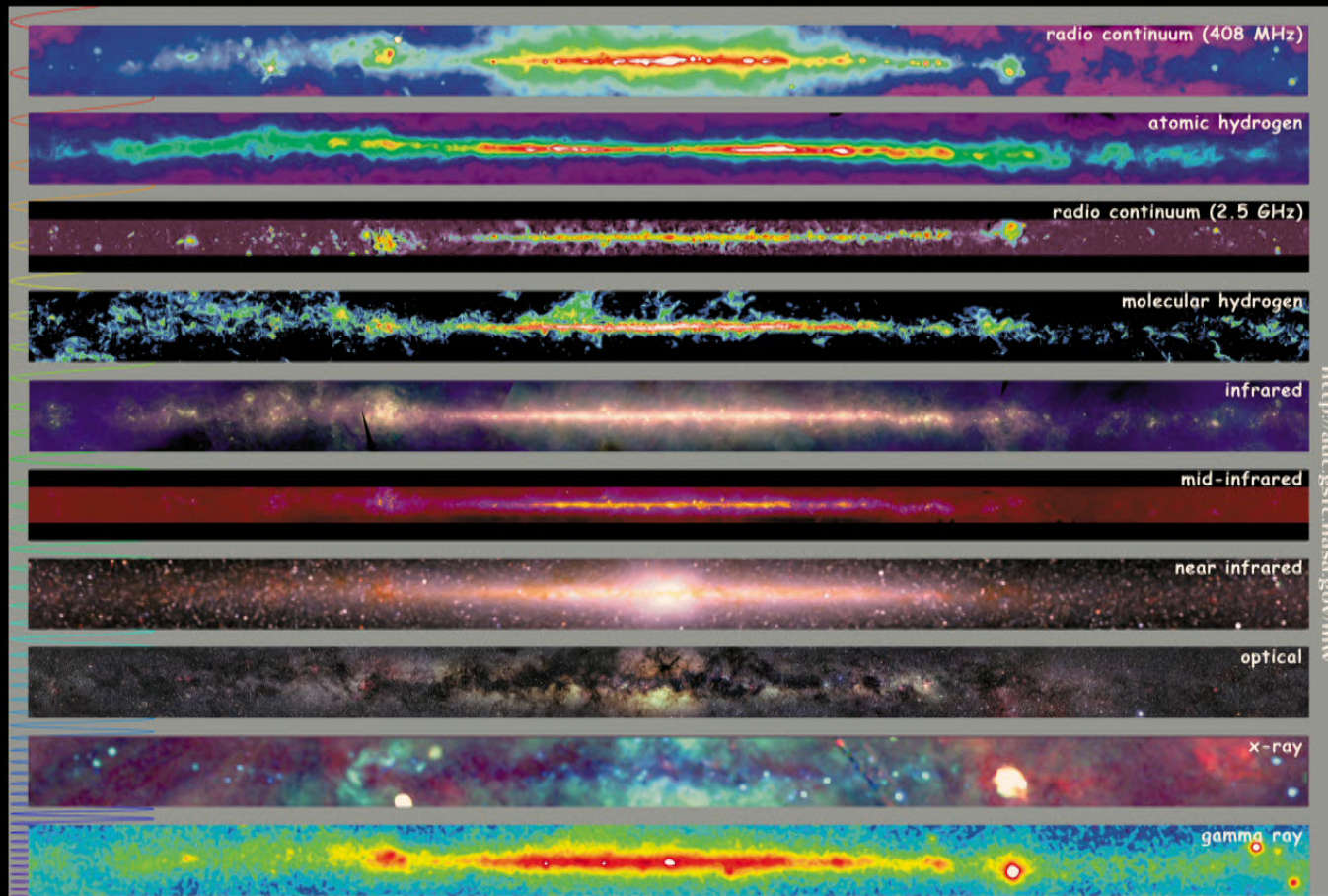
Questions of Specific Interest

- How can we better study **cosmic ray** populations in other galaxies?
 - What can gamma-ray and neutrino observations tell us?
- How is energy distributed among **cosmic rays**, magnetic fields, thermal gas, and radiation in other galaxies?
 - In the Milky Way, energy is evenly distributed.
- What are the primary accelerators of **cosmic rays** in other galaxies?

Questions of Specific Interest

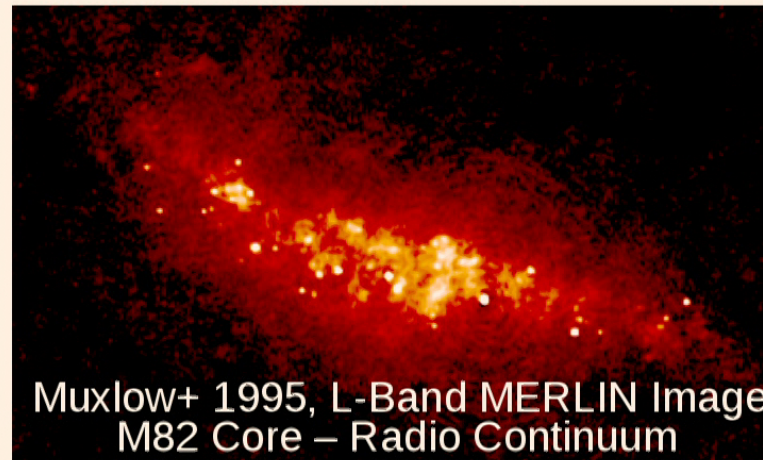
- How can we better study **cosmic ray** populations in other galaxies?
 - What can gamma-ray and neutrino observations tell us?
- How is energy distributed among **cosmic rays**, magnetic fields, thermal gas, and radiation in other galaxies?
 - In the Milky Way, energy is evenly distributed.
- What are the primary accelerators of **cosmic rays** in other galaxies?
 - Can we use gamma-ray observations to distinguish between star forming and AGN activity?

The Multiwavelength Milky Way



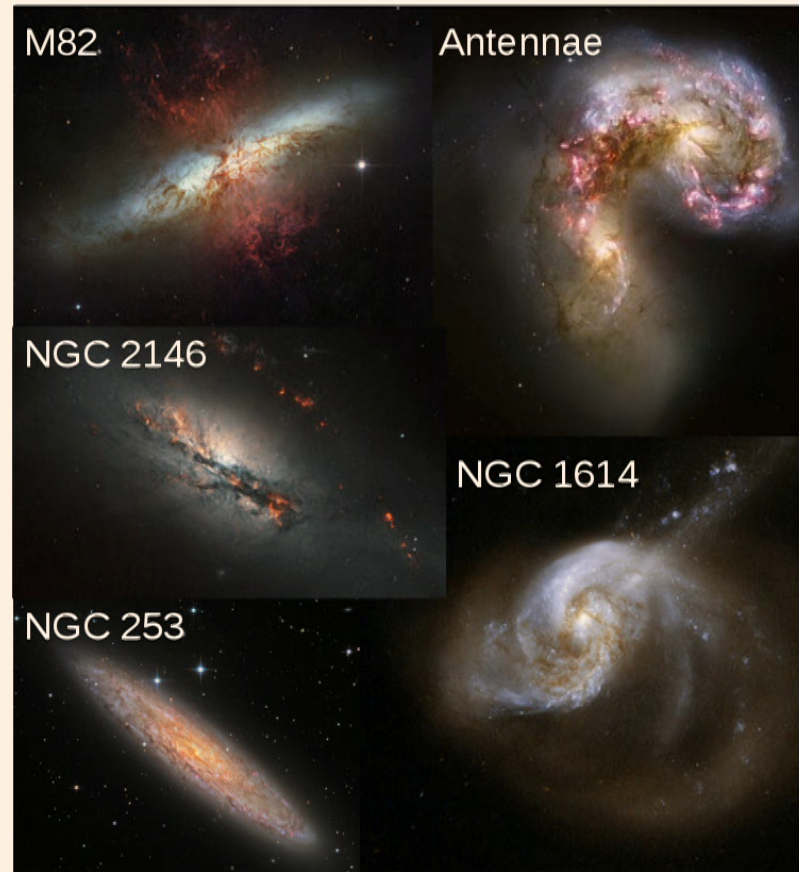
Observational Data

- Radio
 - CR electrons, magnetic fields
- Millimeter
 - Molecular gas content
- Infrared
 - Radiation field
 - Dust temperatures
- Optical
 - ISM pressures, winds
- X-Rays
 - Hot gas content, winds
- Gamma-Rays
 - CR protons & electrons, ISM density
- Neutrinos
 - CR protons & ISM density



Starburst Galaxies

- Definitions:
 - Undergoing high SFR compared to galaxy's long term average.
- Bottom line: high & highly-variable SFRs.
 - Short timescales ($\tau \lesssim 10^8$ yr)
 - 2% of massive galaxies are bursty
 - 10% of total SFRD

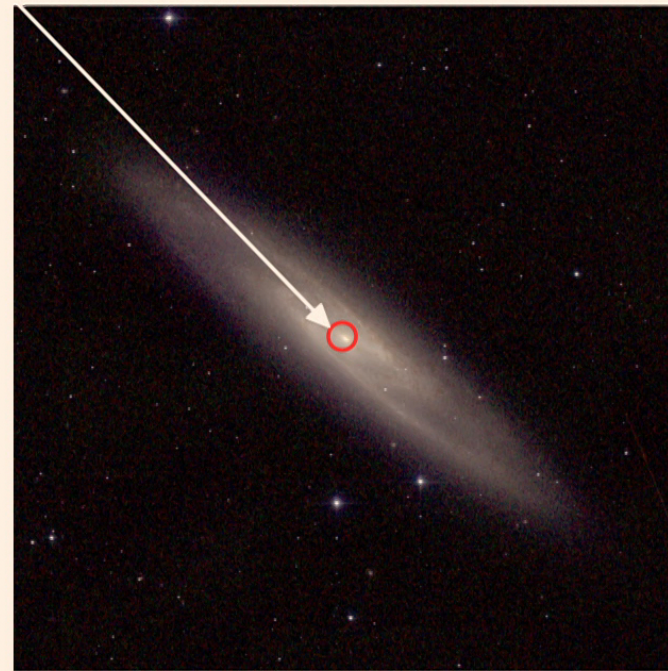


Galaxy Centers

- Circumnuclear starbursts are common for the most luminous galaxies.
- CMZs are characterized by:

- Radius ~ 100 to 300 pc

- Large amounts of dense molecular gas
 - Strong magnetic fields and intense radiation fields
 - Highly variable star-formation rates



Starburst Galaxy: NGC 253

Energies in Starbursts

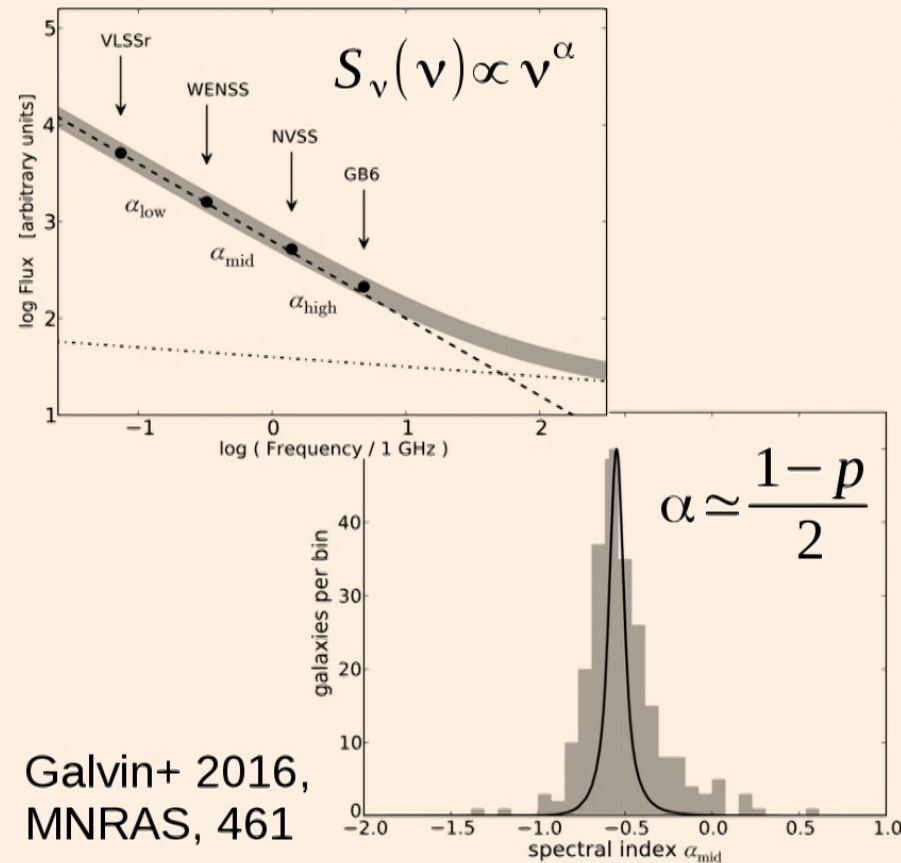
	Star-Forming	Starburst	ULIRGs	Nuclei
SFR ($M_{\odot} \text{ yr}^{-1}$)	~ 1	~ 10	> 100	?
CR Injection ($10^{51} \text{ erg yr}^{-1}$)	~ 0.02	~ 0.1	> 1	~ 10
IR Energy Density (eV cm^{-3})	~ 1	> 100	$> 10^4$	$> 10^6$
ISM Density (cm^{-3})	~ 1	> 100	$> 10^4$	$> 10^5$
Magnetic Field (mG)	~ 0.005	> 0.1	> 1	~ 10

Tova M. Yoast-Hull

Apr 2019, 19 / 27

Starburst Galaxies: Radio

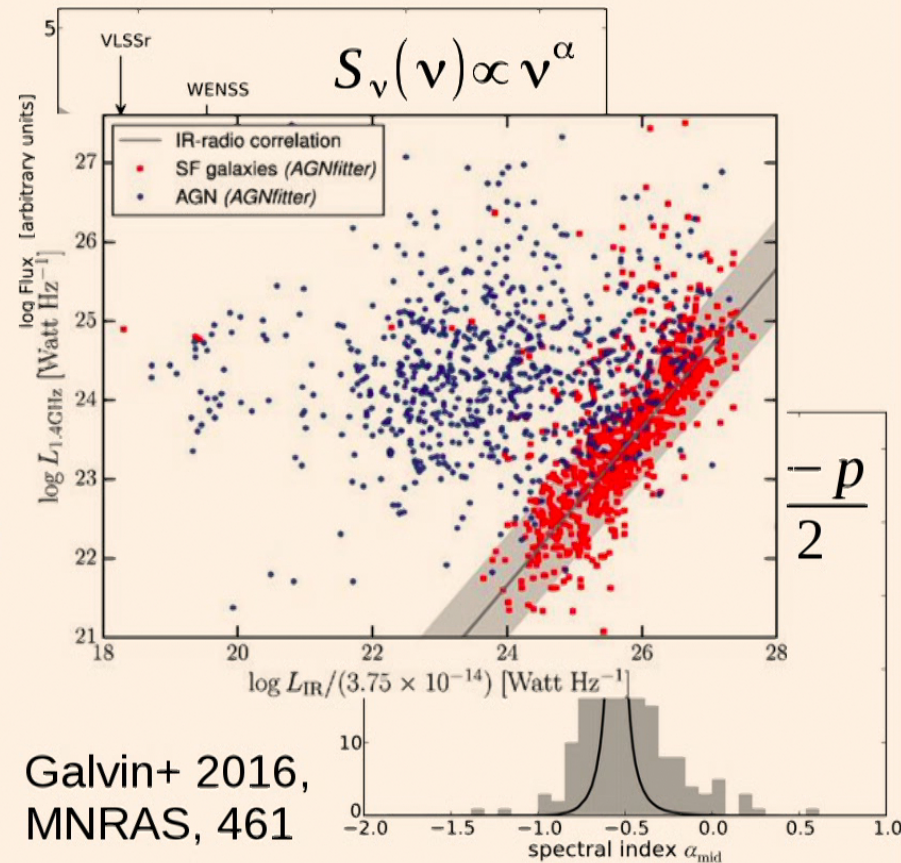
- At 1.4 GHz (21 cm), non-thermal synch dominates the radio
 - Average spectral index: $\alpha = -0.7$
 - Average thermal fraction: $\sim 10\%$
- Higher magnetic field strengths:
 - $B > 100 \mu\text{G}$
- Correlated with FIR



Galvin+ 2016,
MNRAS, 461

Starburst Galaxies: Radio

- At 1.4 GHz (21 cm), non-thermal synch dominates the radio
 - Average spectral index: $\alpha = -0.7$
 - Average thermal fraction: $\sim 10\%$
- Higher magnetic field strengths:
 - $B > 100 \mu\text{G}$
- Correlated with FIR

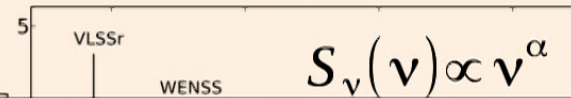


Tova M. Yoast-Hull

Apr 2019, 20 / 27

Starburst Galaxies: Radio

- At 1.4 GHz (21 cm),

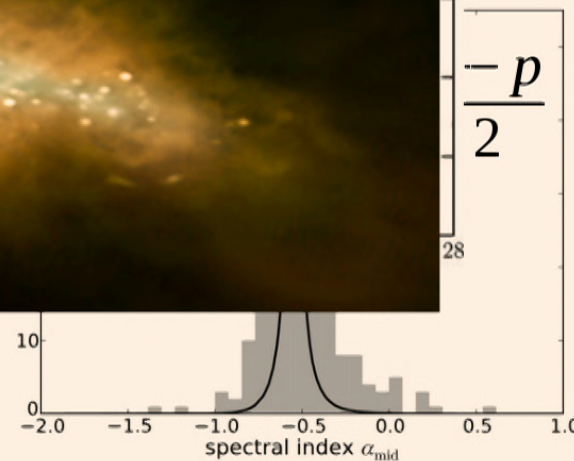


J. Marvil, VLA 3 GHz

- H_I st

- Correlated with FIR

Galvin+ 2016,
MNRAS, 461



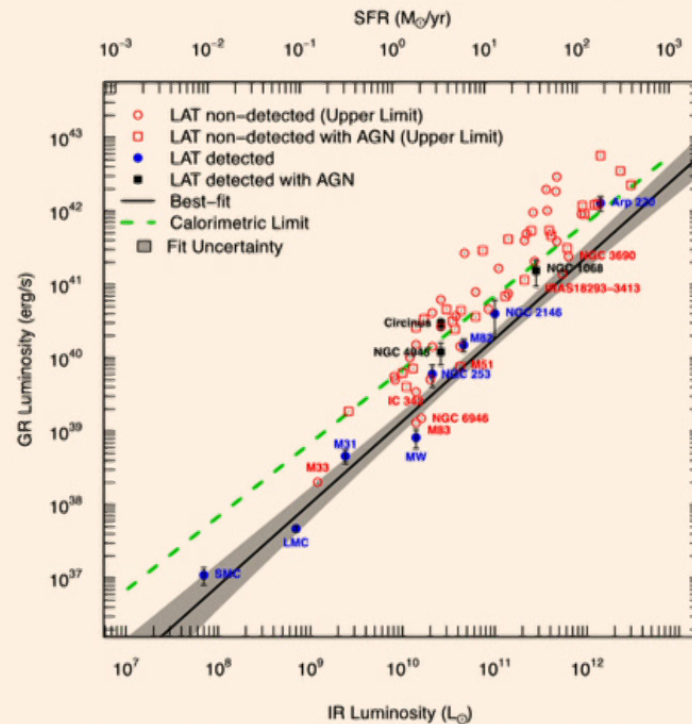
Tova M. Yoast-Hull

Apr 2019, 20 / 27

Starburst Galaxies: Gamma Rays

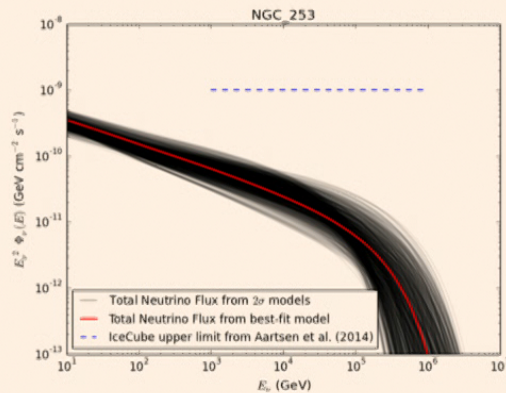
- Gamma-ray detections:
 - Fermi: M82, NGC 253, NGC 4945★, NGC 1068★, NGC 2146, Circinus★, Arp 220
 - TeV: M82 (Veritas) & NGC 253 (HESS)
- Hard gamma-ray spectral indices.
 - $p \sim 2.2 - 2.4$
- Both hadronic & leptonic contributions to total flux.

★ = Non-Jetted AGN



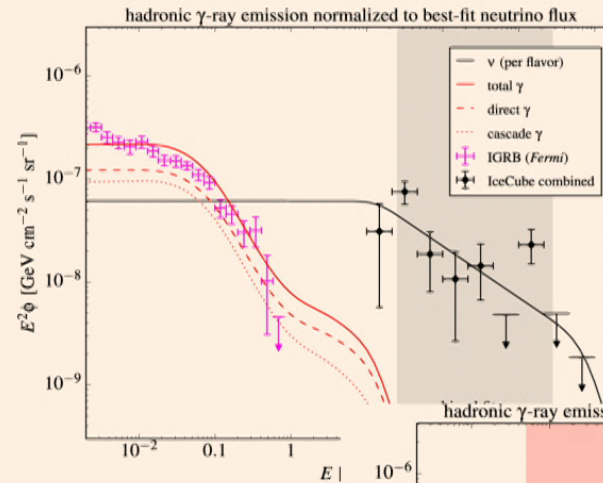
Rojas-Bravo & Araya 2016,
MNRAS, 463

Starburst Galaxies: Neutrinos

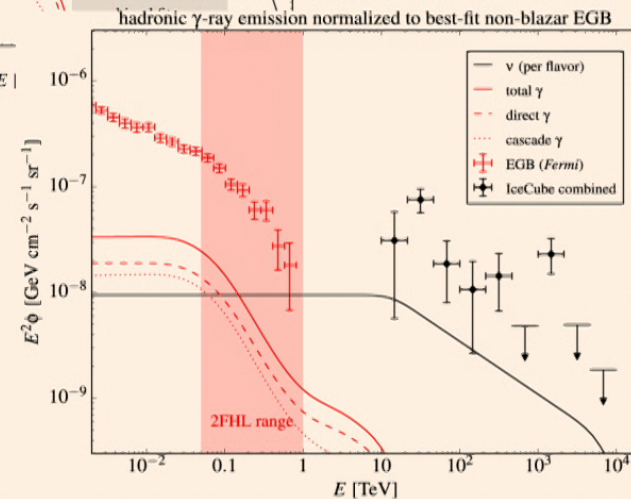


Eichmann & Tjus 2016
ApJ, 821

- Hadronic channels only!
- Probable contribution of star-forming galaxies to IceCube neutrinos $\lesssim 10\%$.



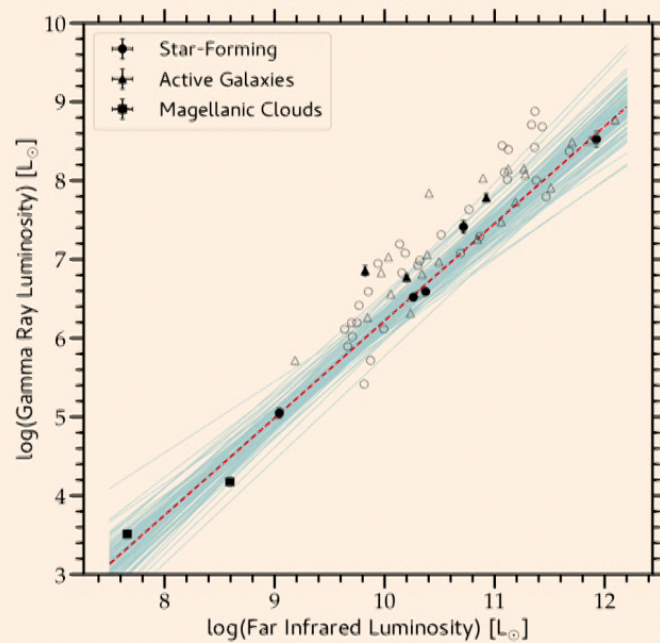
K. Bechtol + 2017
ApJ, 836



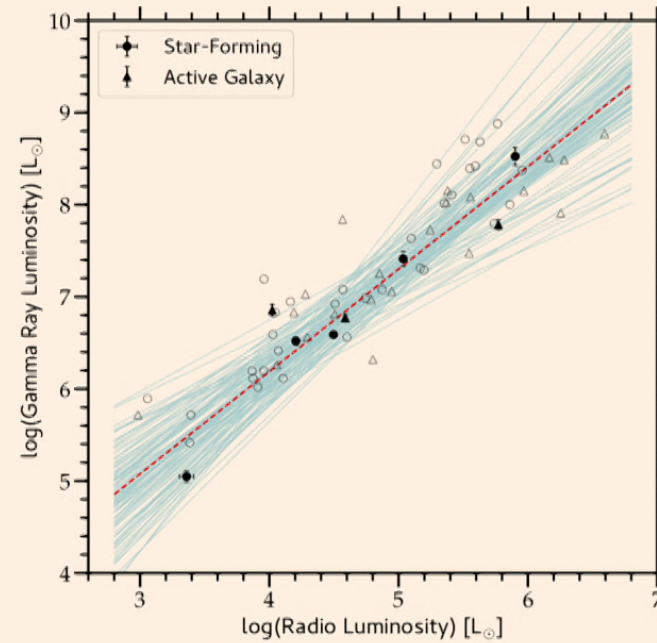
Tova M. Yoast-Hull

Apr 2019, 22 / 27

Galaxy Correlations



Yoast-Hull & Murray
2019, MNRAS

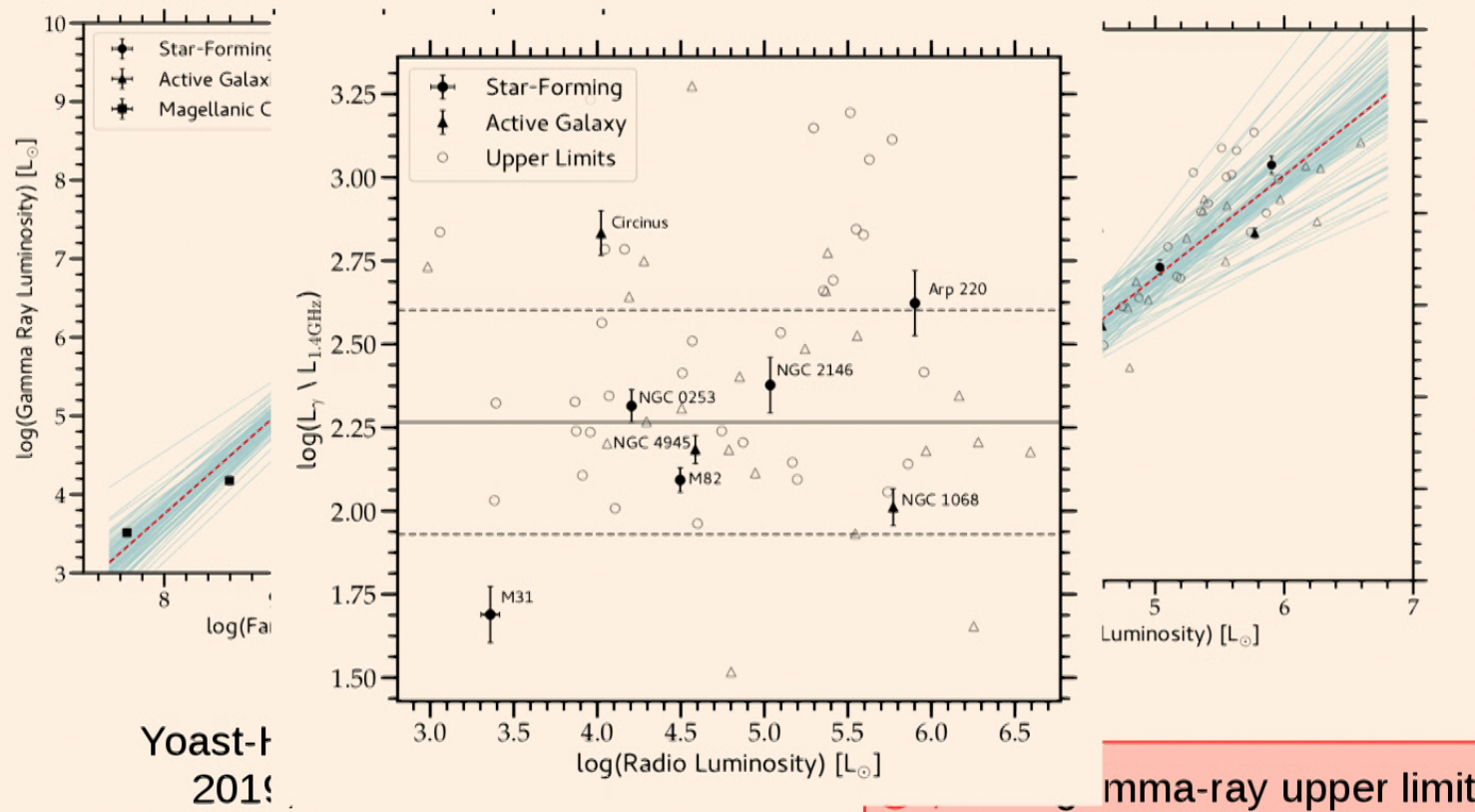


○ / △ = gamma-ray upper limit

Tova M. Yoast-Hull

Apr 2019, 23 / 27

Galaxy Correlations



Yoast-Hull
2019

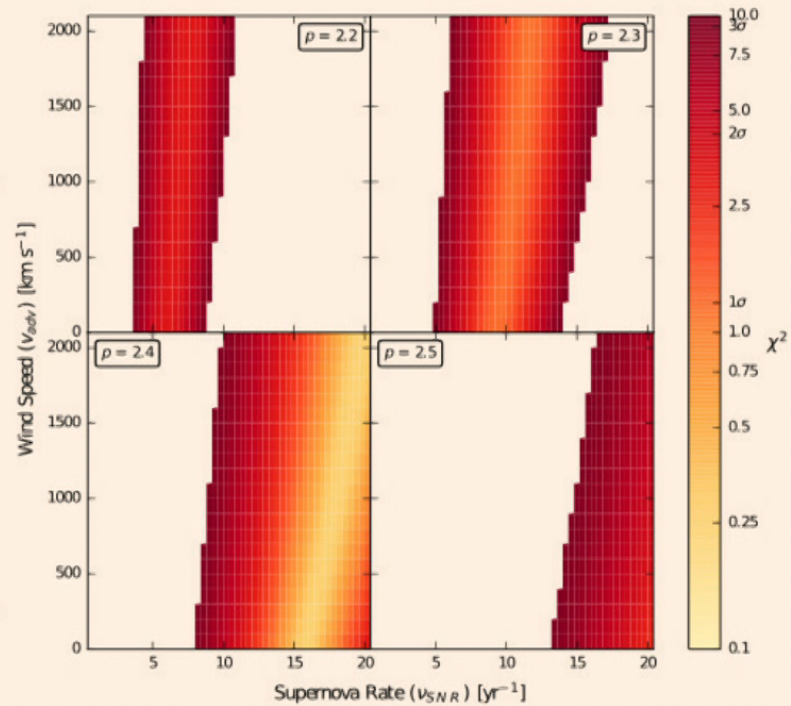
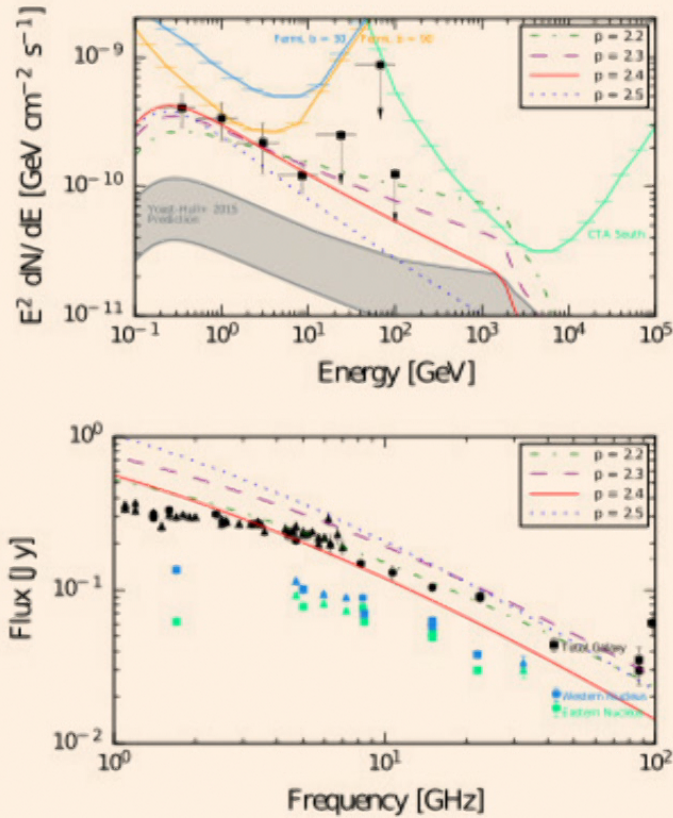
gamma-ray upper limit

Tova M. Yoast-Hull

Apr 2019, 23 / 27

Hidden Active Galactic Nuclei

Yeast-Hull+ 2017,
MNRAS, 469L, 89

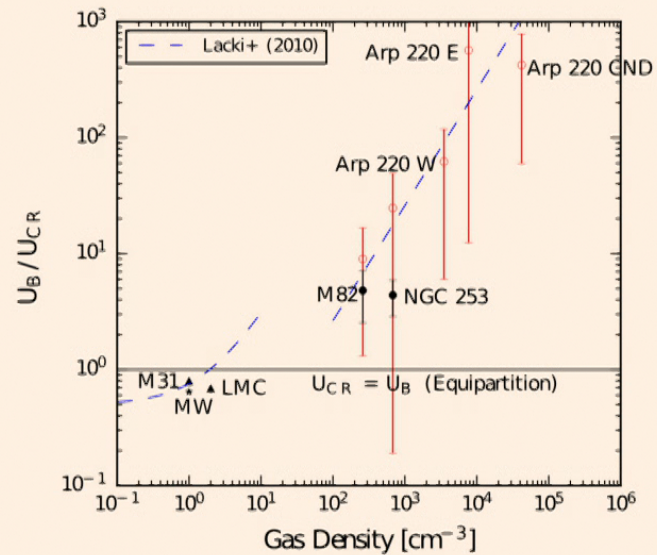
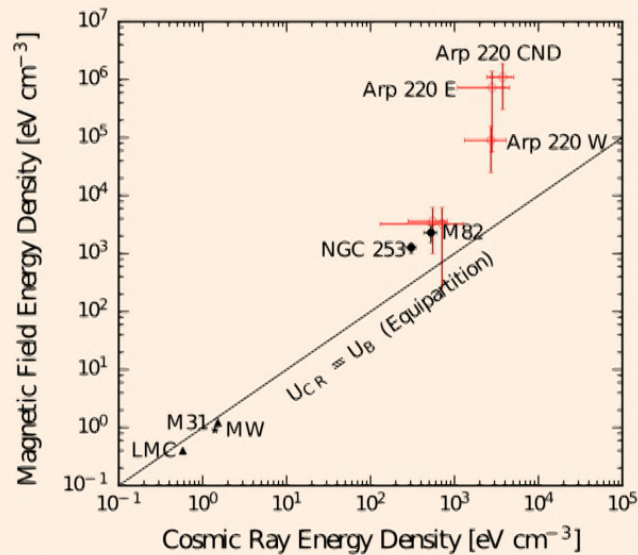


Tova M. Yoast-Hull

Apr 2019, 24 / 27

Energy Densities

Yoast-Hull+ 2016, MNRAS, 457, L29



$$U_{CR} = \int E N(E) dE$$

$$U_B = \frac{B^2}{8\pi}$$

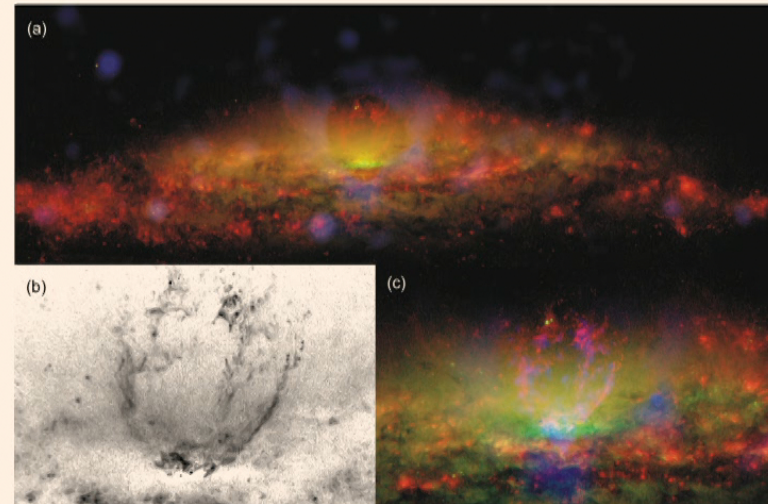
$$U_{IR} = \frac{L_{IR}}{4\pi R^2 c}$$

Tova M. Yoast-Hull

Apr 2019, 25 / 27

Feedback From Cosmic Rays

- CRs heat molecular ISM, leading to quenching of star formation.
- Starburst galaxies produce outflows
 - Removes mass & energy from ISM
 - Magnetic fields & cosmic rays can also be removed
- Primary mechanism by which energy is deposited into the intergalactic medium



NGC 3079
Veilleux+ 2005, ARA&A, 43

Cosmic Ray Astrophysics

- **Joint modeling & observations** of gamma-rays and radio emission are powerful probes of **cosmic ray** populations in galaxies.
 - Gamma-rays provide critical information about CR proton populations & can be used as **diagnostics for hidden AGN**.
- In starburst galaxies, a larger fraction of energy goes into **magnetic fields**.
 - Energy in **cosmic rays** is redeposited into the interstellar and intergalactic media.
 - For alternative diagnostics of magnetic fields look to the turbulent energy densities.
- The traditional **radio – gamma-ray connection** breaks down in extreme systems.
 - Accounting for trapped radiation and **optically thick** radiation fields is critical.