Star-Forming Galaxies As Sources of High Energy Neutrinos

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5 May 2015

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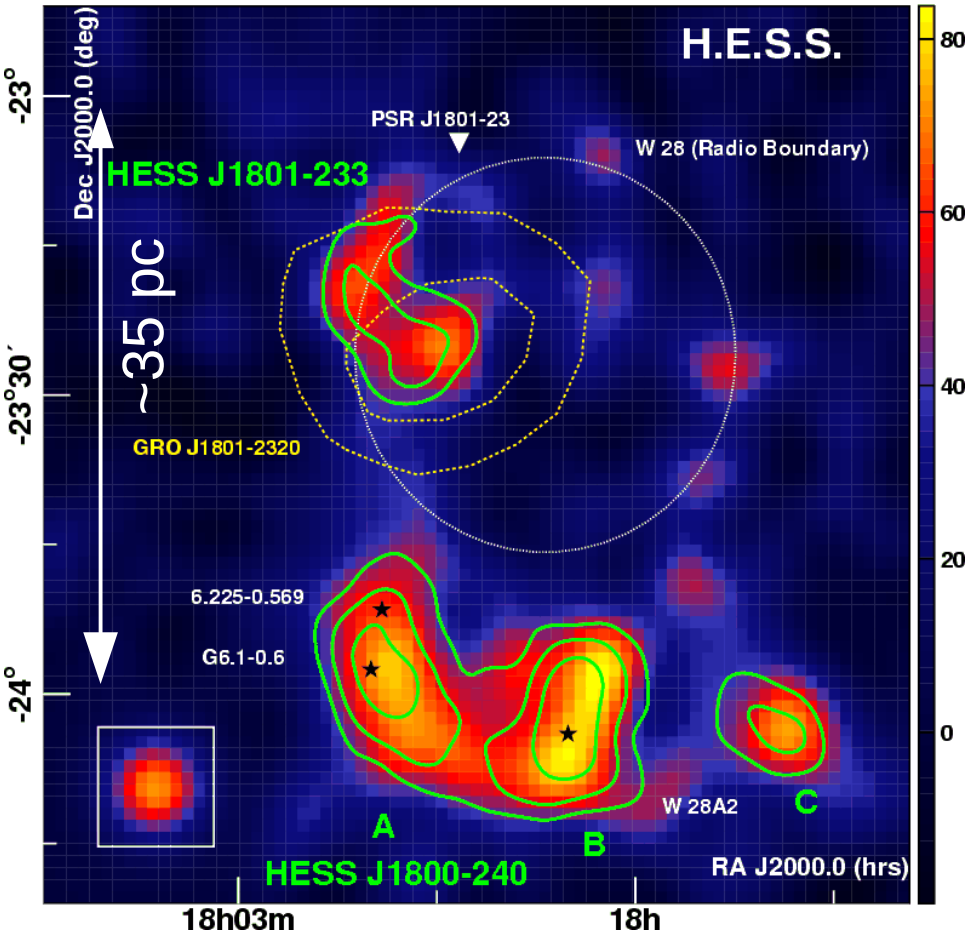
Funded by: Center for Magnetic Self-Organization & Wisconsin IceCube Particle Astrophysics Center

Cosmic Ray Populations in Galaxies

- Significant fraction of energy from supernovae goes into CRs and is redistributed via:
  - Interactions with the ISM (heating)
  - Launching of galactic winds (cooling)
- CRs detected at Earth were scrambled by the galactic B-field; other messengers:
  - Radio (CR electrons & magnetic field)
  - Gamma-rays, neutrinos (CR protons & ISM density)
- Accelerators of CRs up to PeV energies are still unknown.



Supernova Remnant W28
Aharonian+ 2008, A&A, 481

Questions of Specific Interest

- Are high energy gamma-rays good tracers of astrophysical neutrinos in extreme starbursts?
- Are starburst galaxies proton calorimeters?
  - How important are advective losses in comparison to energy losses?
- Does equipartition of cosmic rays & magnetic fields hold in other galaxies?
  - How applicable are the magnetic field strengths estimated from minimum energy arguments?

YEGZ Starburst Model

Cosmic rays
are accelerated
by supernova
remnants.

Yoast-Hull+ 2013, ApJ, 768

YEGZ Starburst Model

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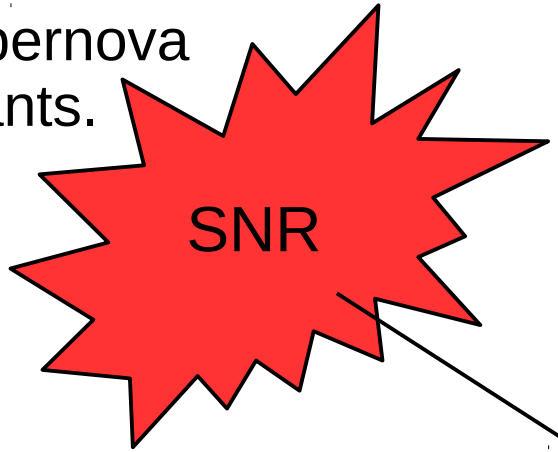


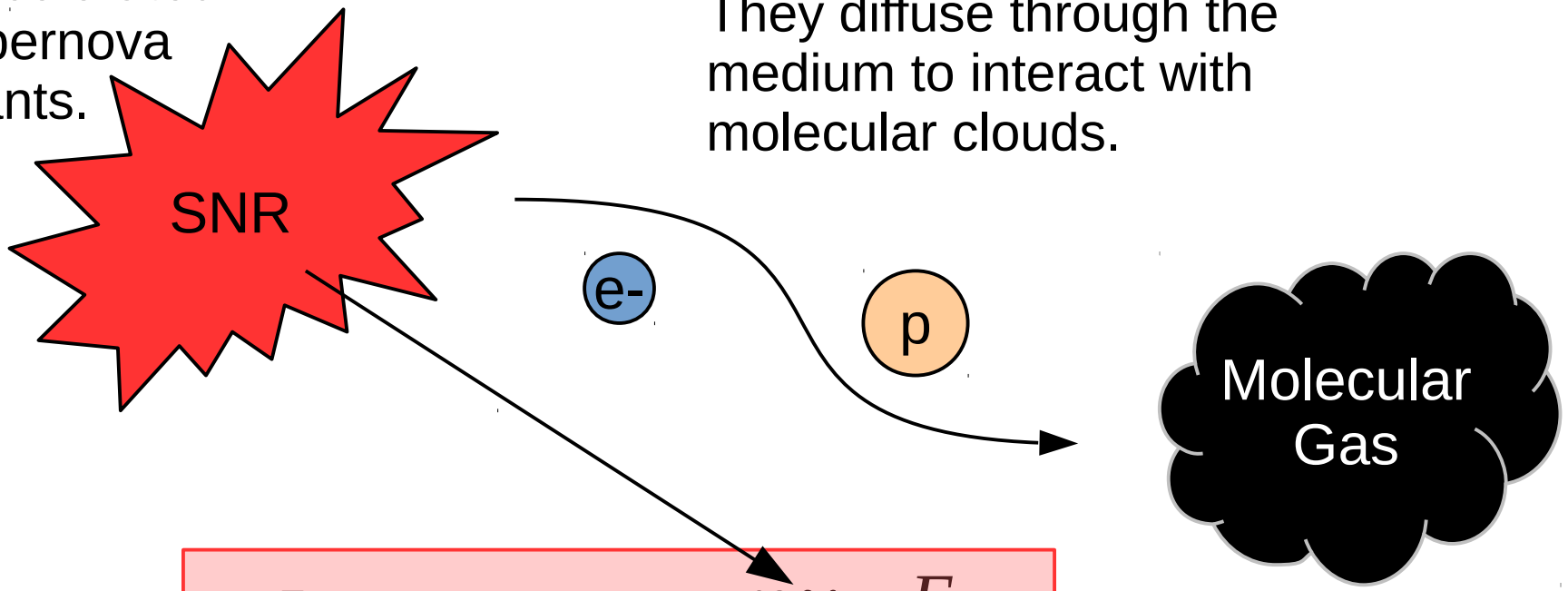
$$\int_{E_{min}}^{E_{max}} Q(E)\, E\, dE = \frac{\eta \nu_{SN} E_{51}}{V}$$

Yoast-Hull+ 2013, ApJ, 768

YEGZ Starburst Model

Cosmic rays are accelerated by supernova remnants.

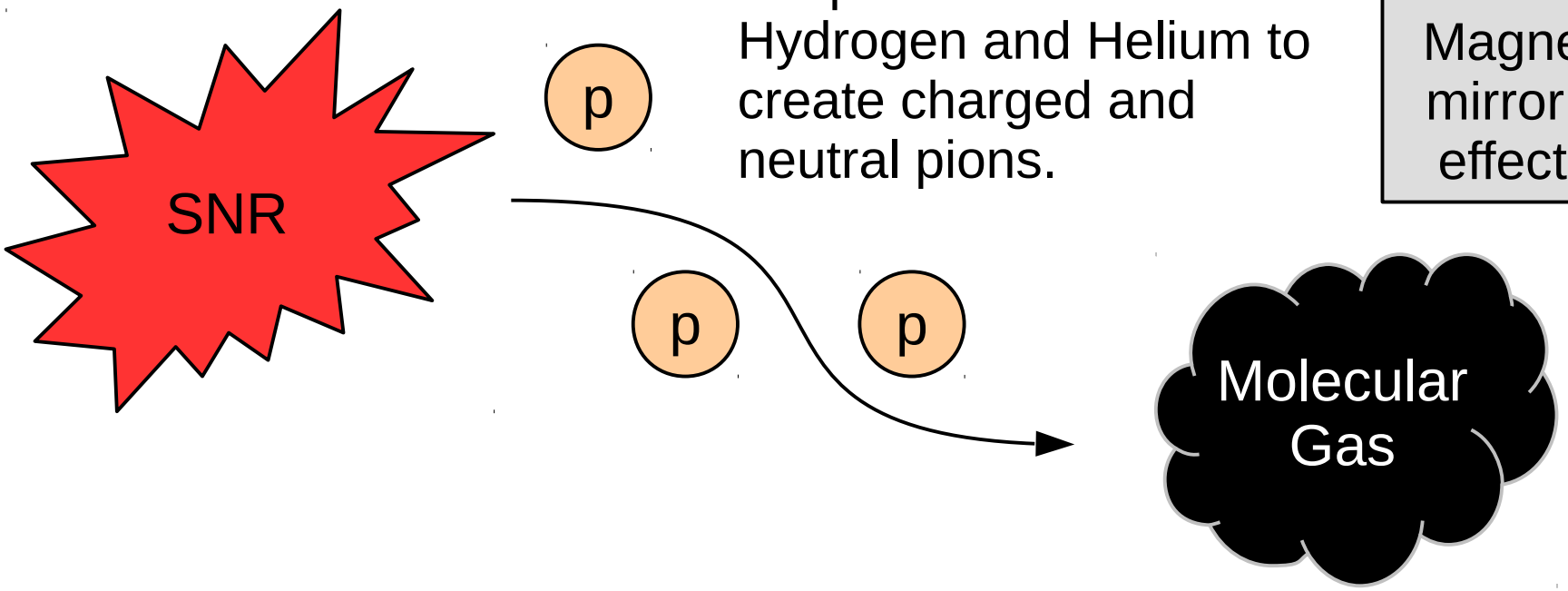
They diffuse through the medium to interact with molecular clouds.



$$\int_{E_{min}}^{E_{max}} Q(E)\,E\,dE = \frac{\eta \nu_{SN} E_{51}}{V}$$

Yoast-Hull+ 2013, ApJ, 768

YEGZ Starburst Model – Hadrons

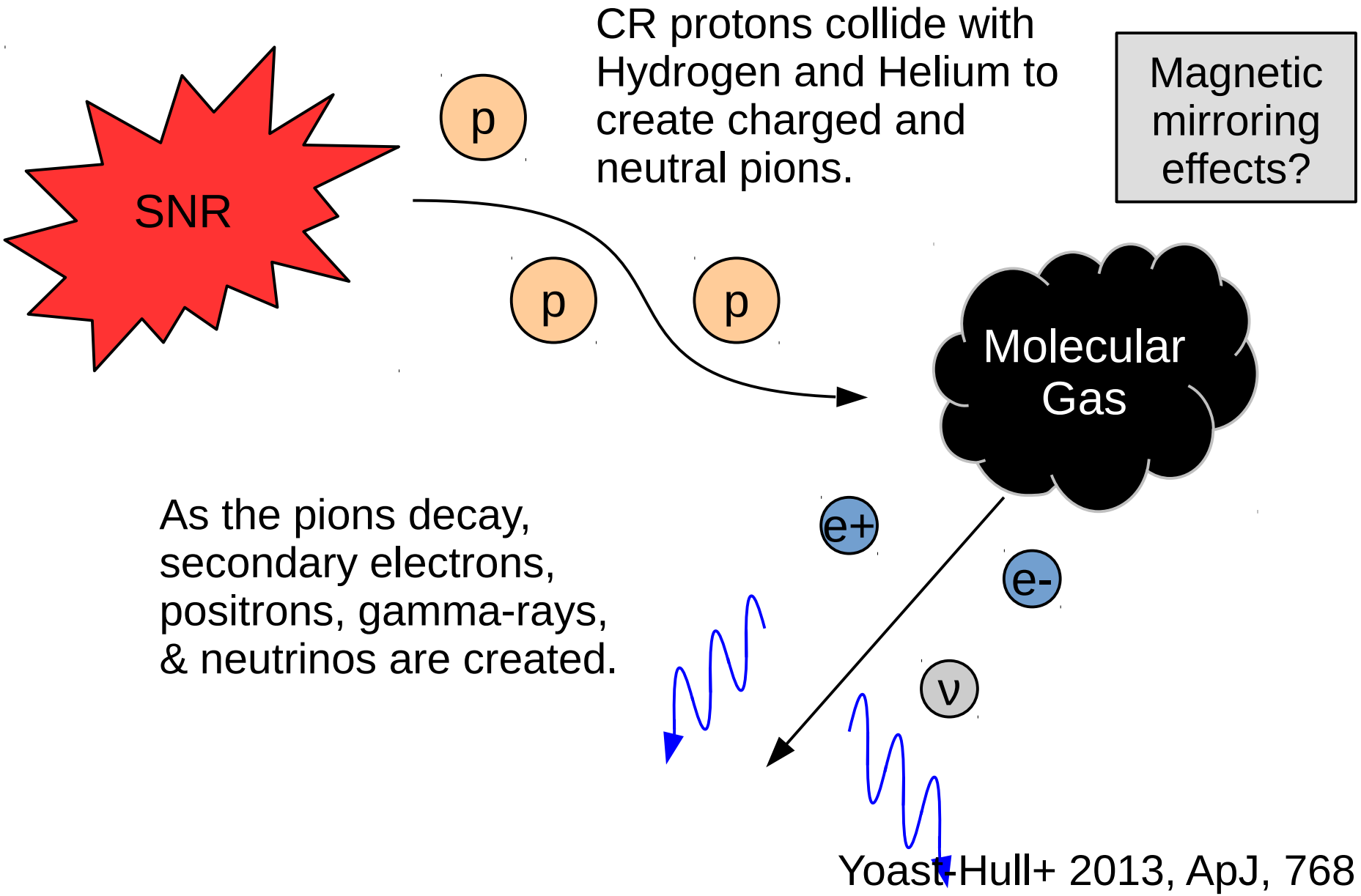


CR protons collide with Hydrogen and Helium to create charged and neutral pions.

Magnetic mirroring effects?

Yoast-Hull+ 2013, ApJ, 768

YEGZ Starburst Model – Hadrons



Yoast-Hull+ 2013, ApJ, 768

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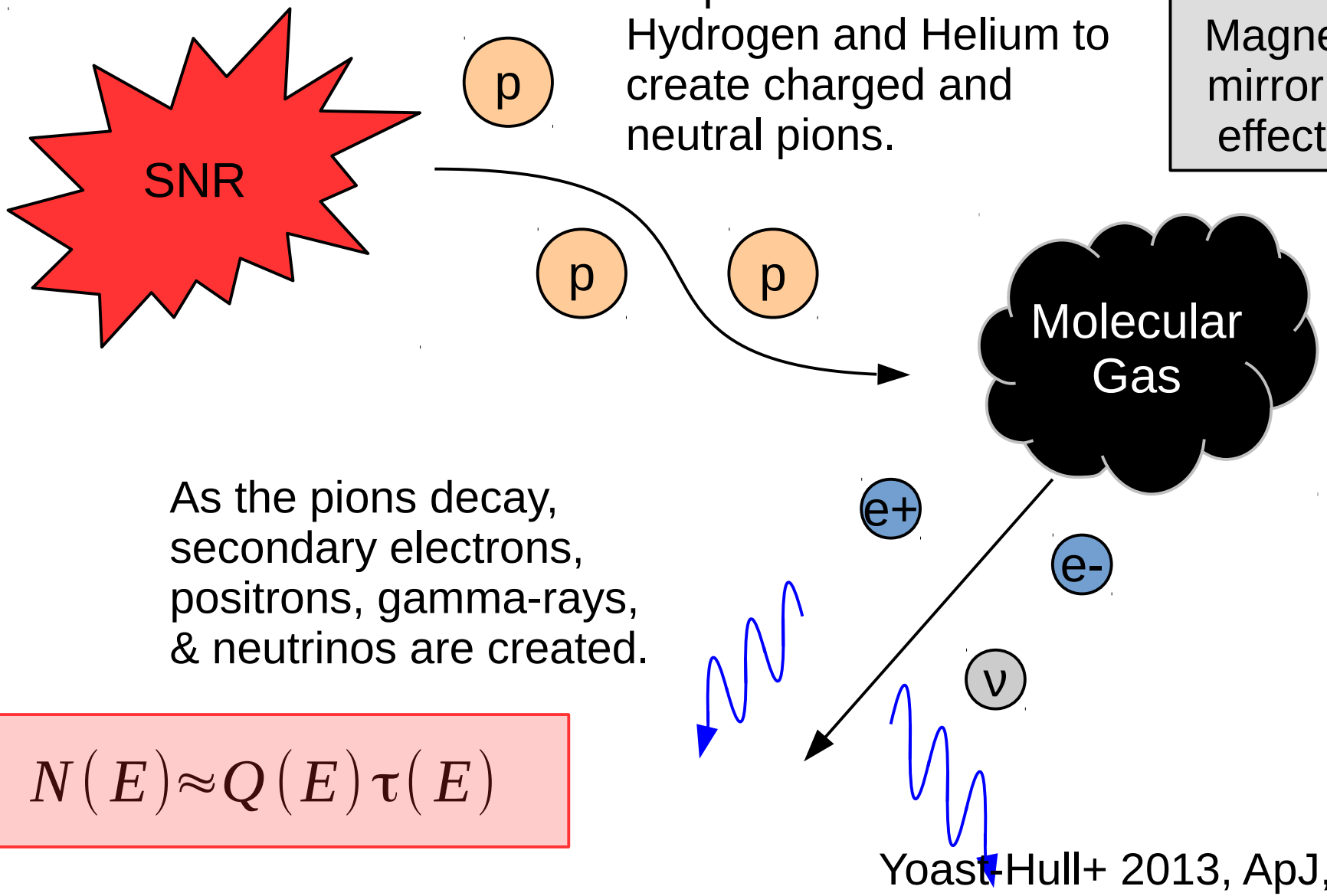
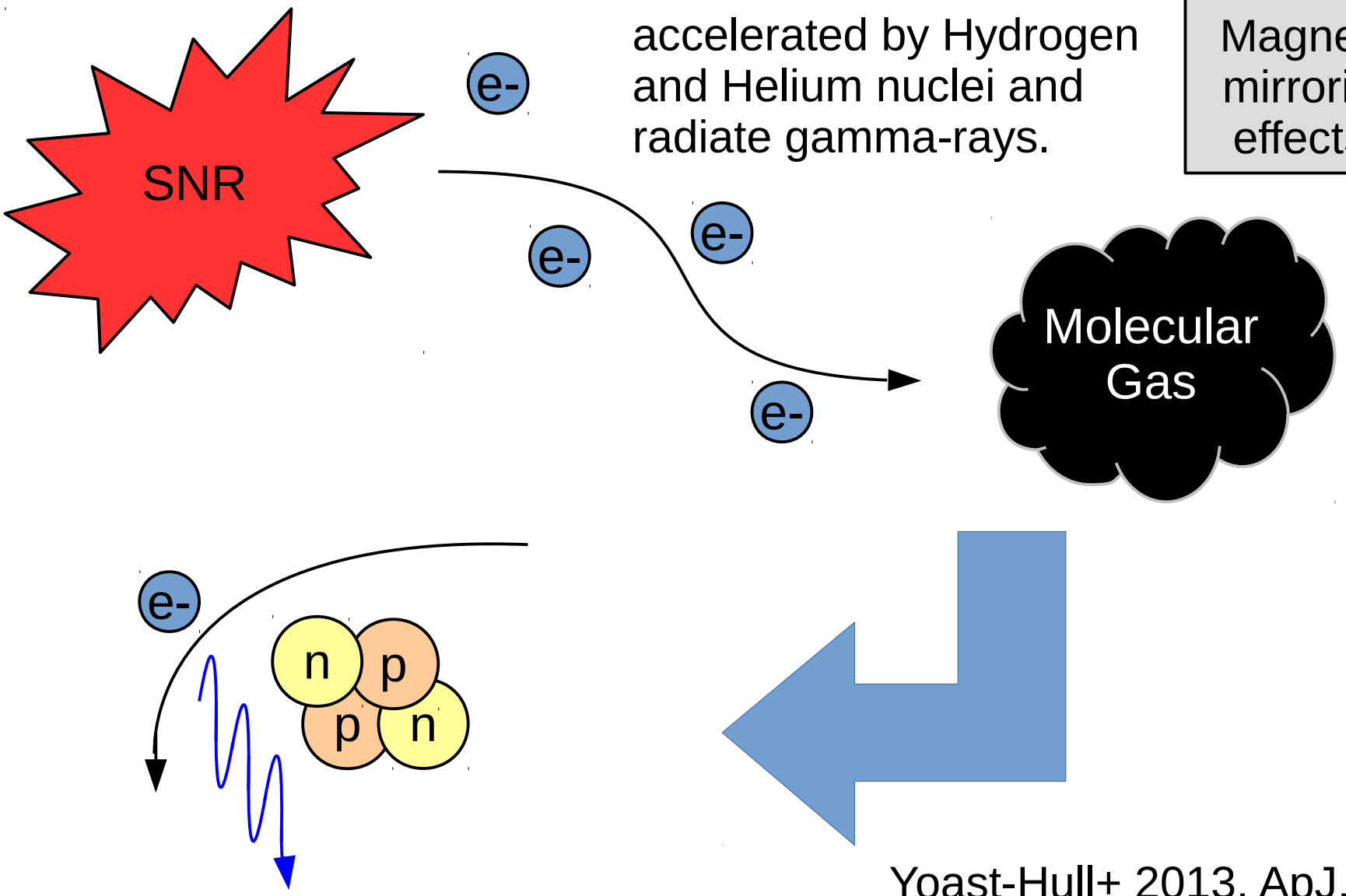


YEGZ Starburst Model – Leptons

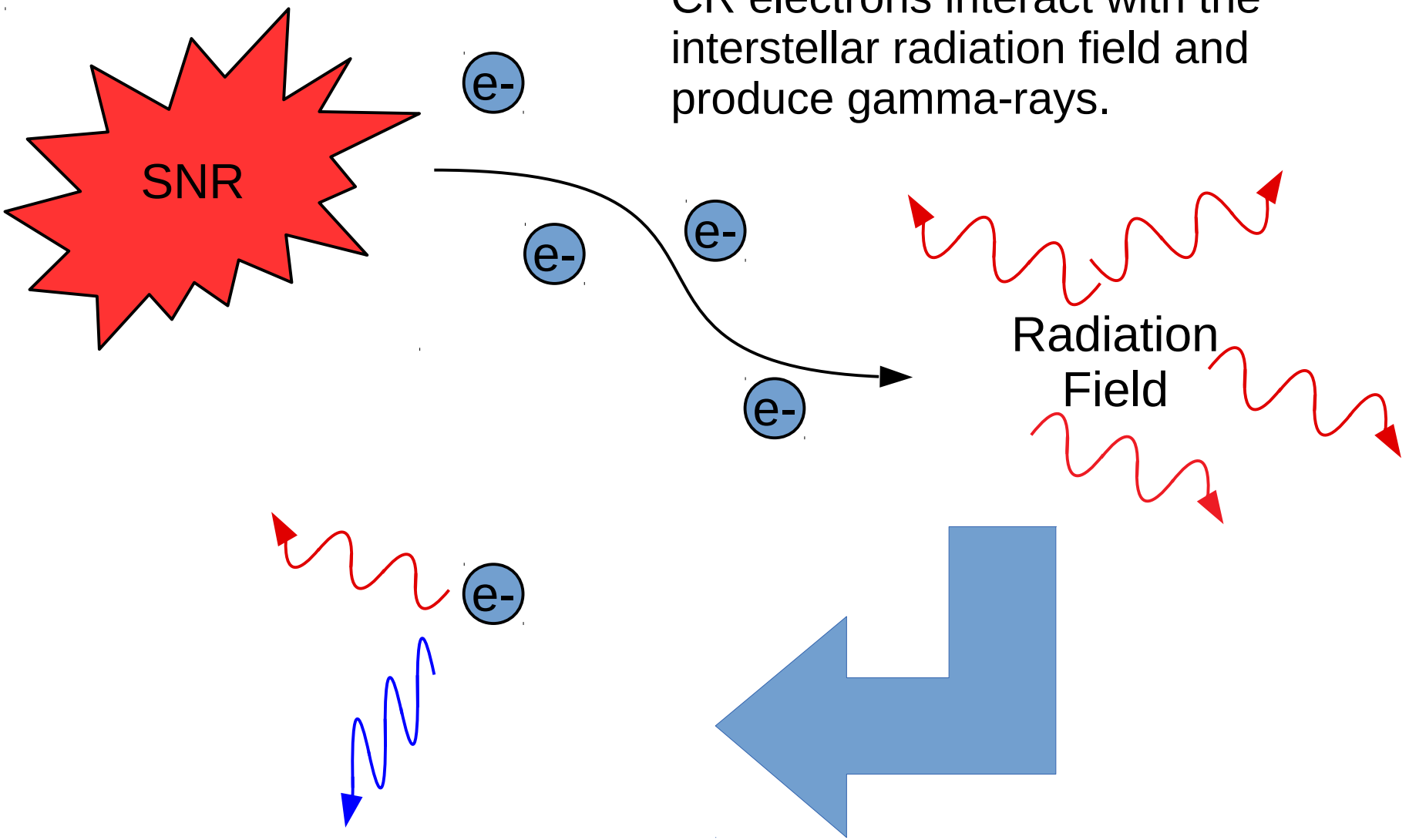


CR electrons are accelerated by Hydrogen and Helium nuclei and radiate gamma-rays.

Magnetic mirroring effects?

Yoast-Hull+ 2013, ApJ, 768

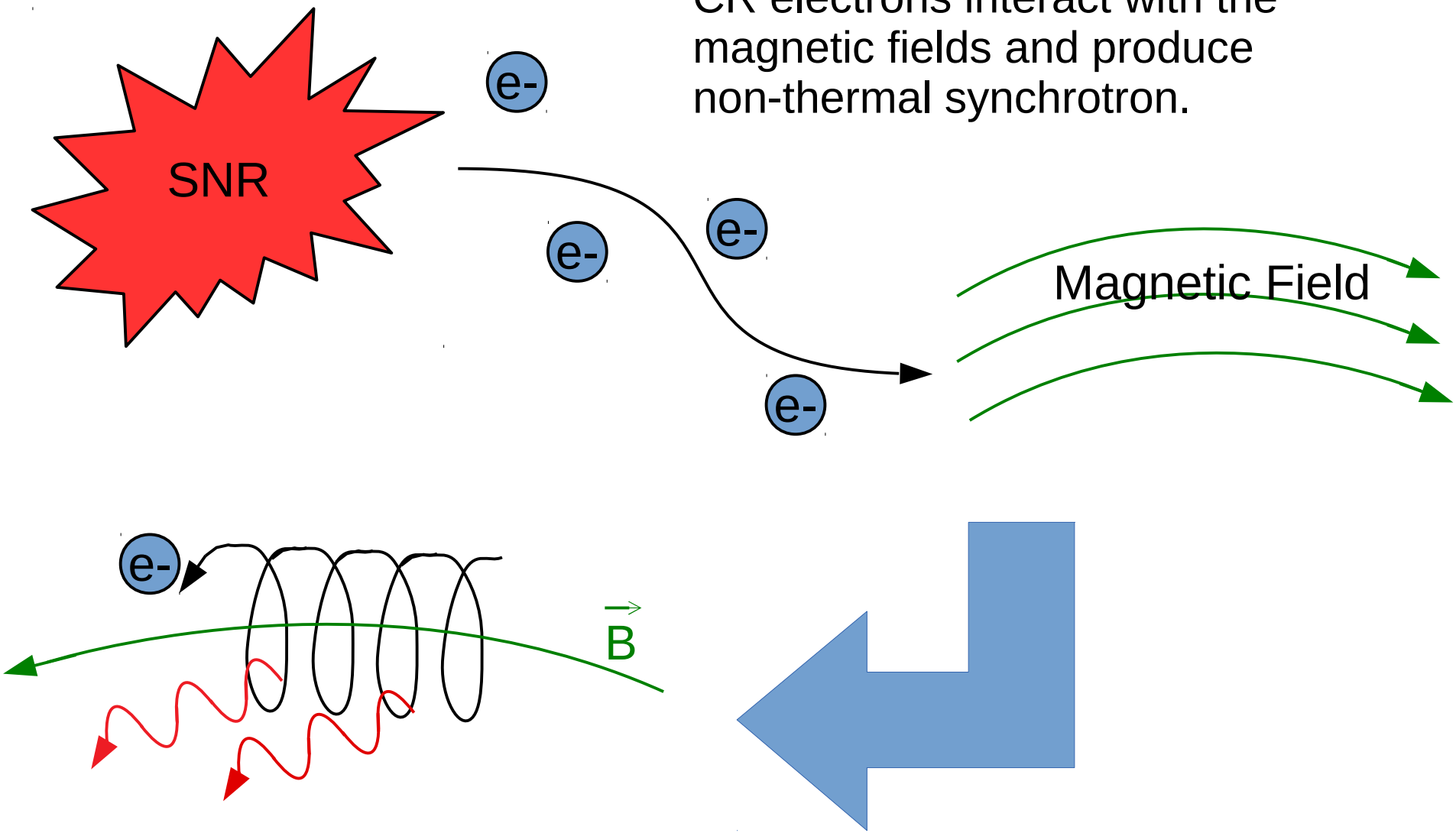
YEGZ Starburst Model – Leptons



Yoast-Hull+ 2013, ApJ, 768

YEGZ Starburst Model – Leptons

CR electrons interact with the magnetic fields and produce non-thermal synchrotron.



Yoast-Hull+ 2013, ApJ, 768

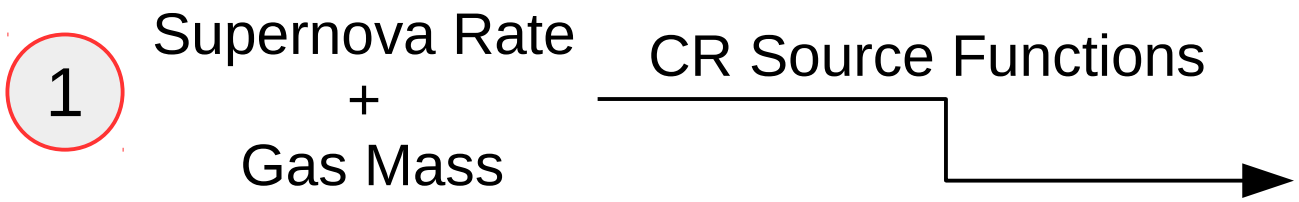
Model Overview

Model Overview

1

Supernova Rate
+
Gas Mass

Model Overview



Model Overview

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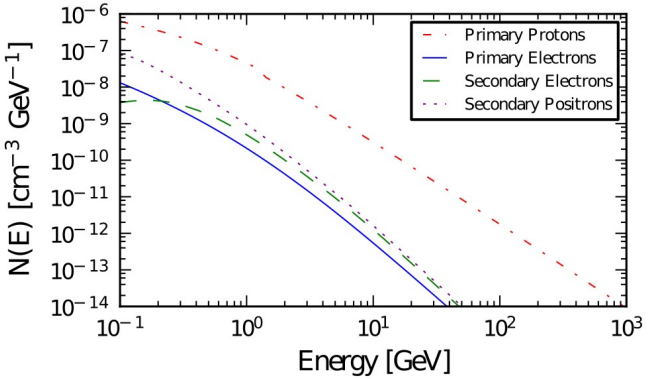
CR Source Functions



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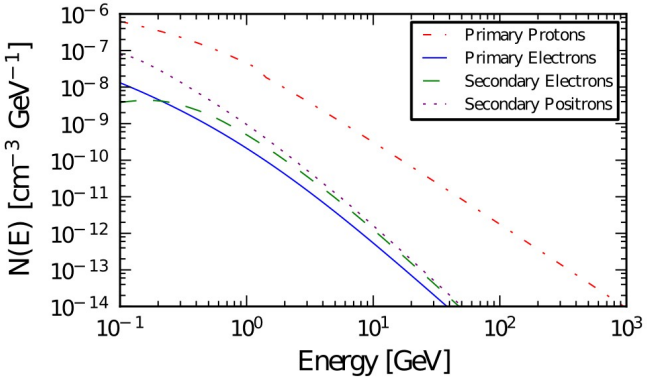

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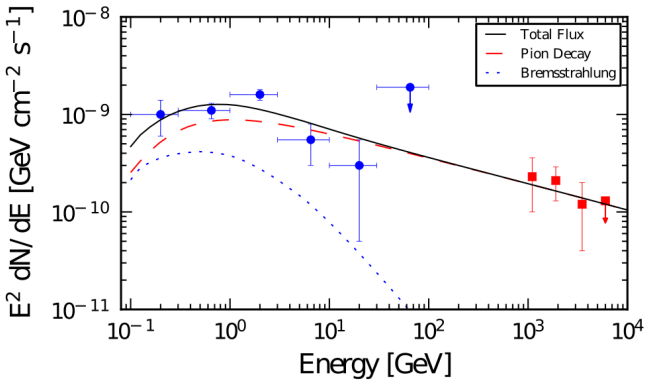

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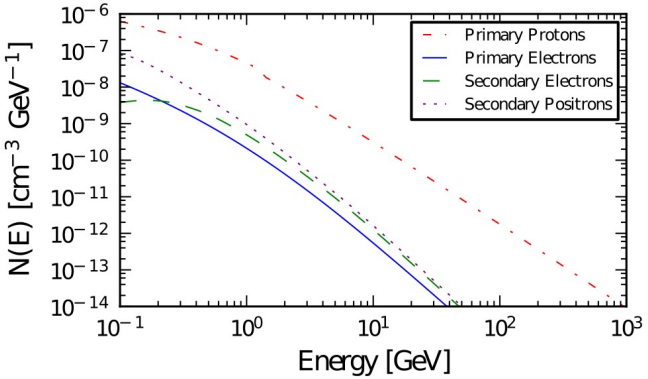

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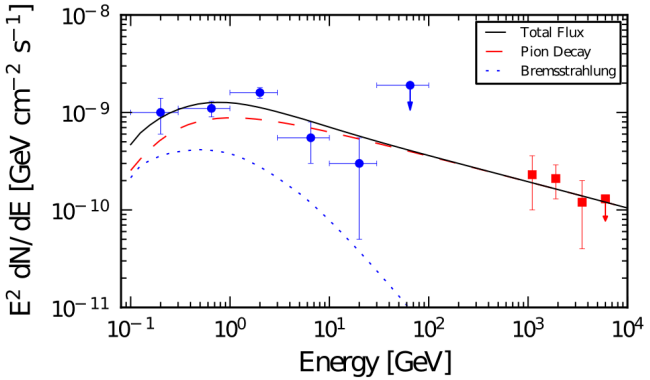

CR Protons

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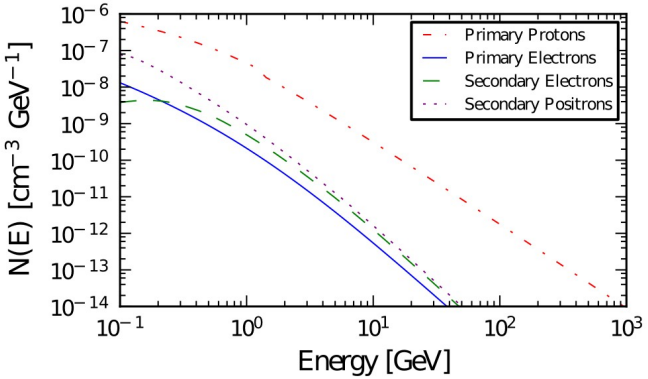

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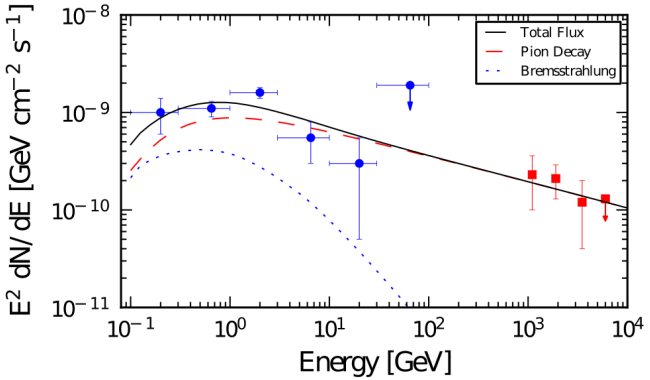

CR Protons

Spectral Index
+
Wind Speed

Model Overview

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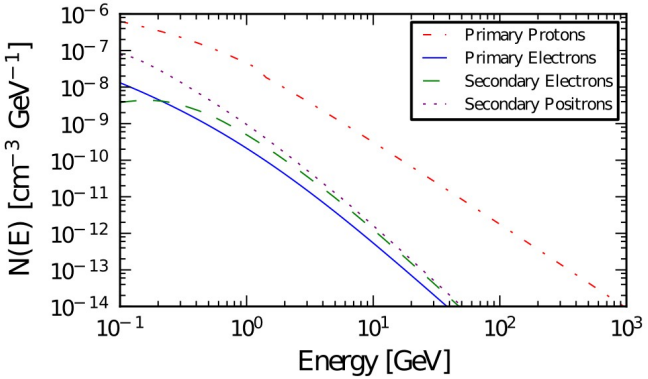

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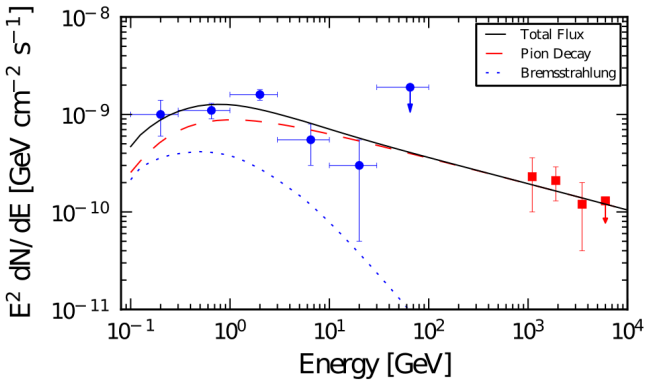

CR Protons

Spectral Index
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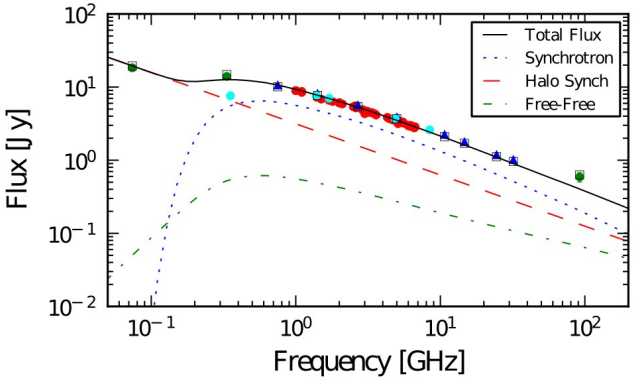
Wind Speed

3



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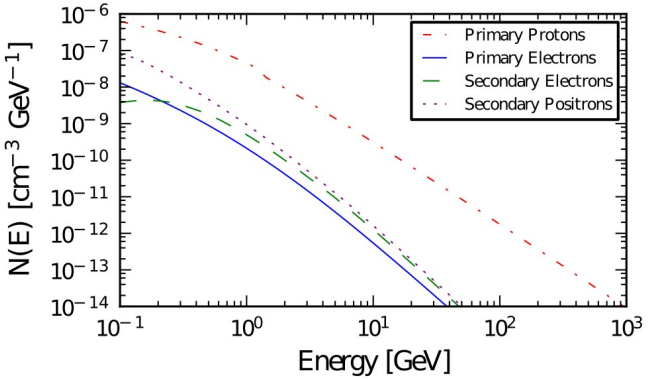

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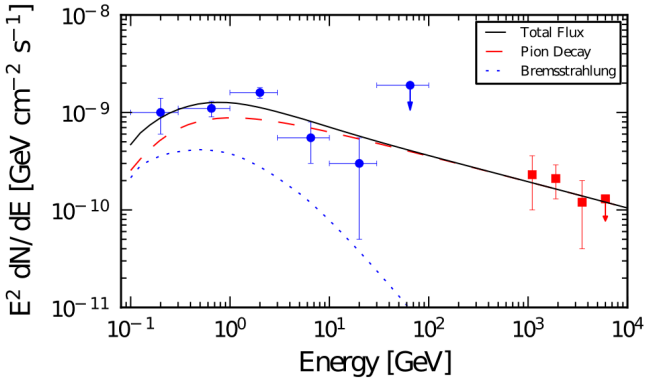

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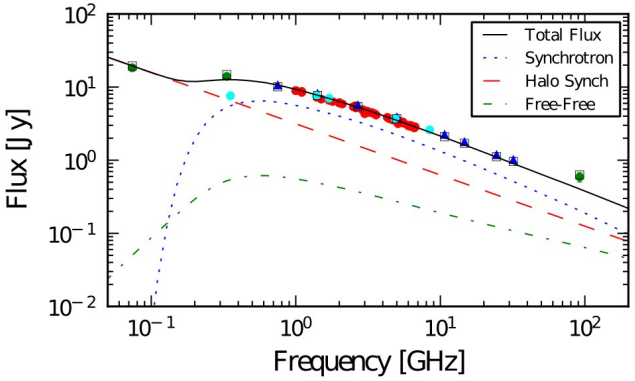

CR Electrons

Model Overview

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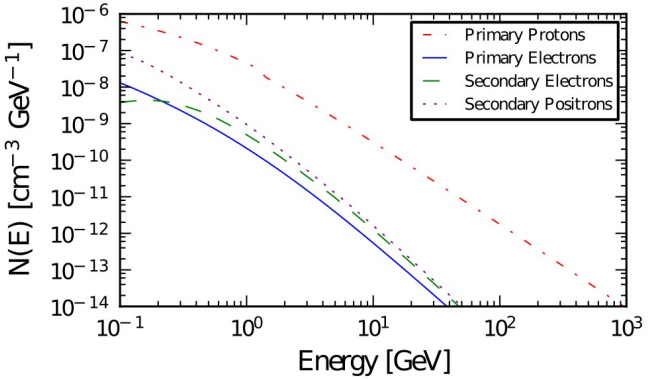
CR Source Functions



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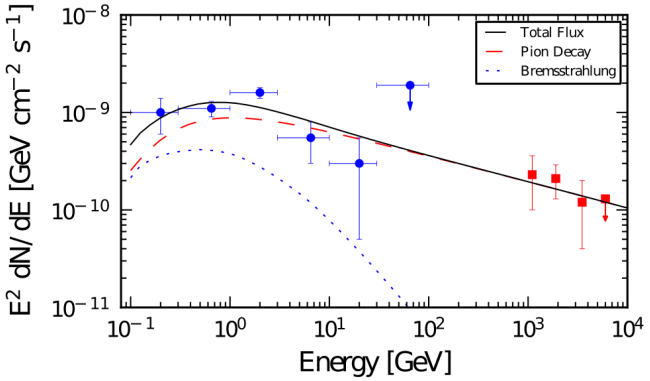

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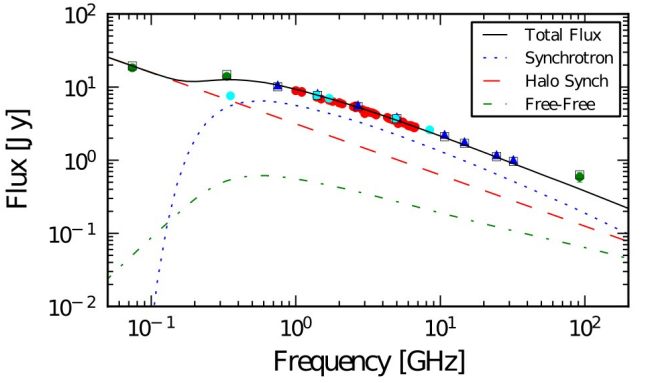


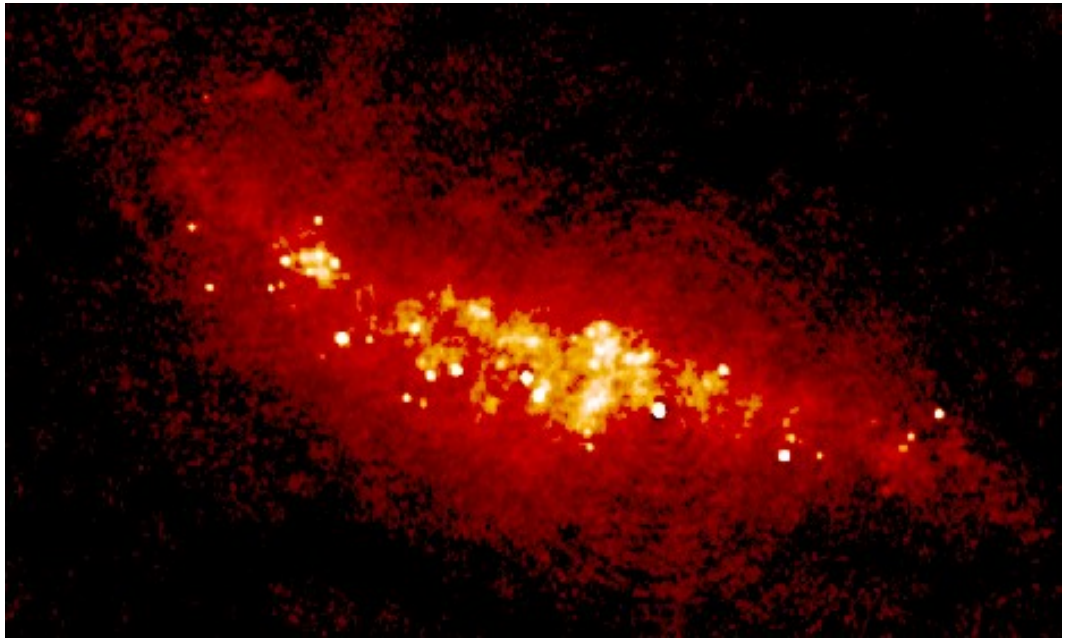
CR Electrons

Magnetic Field Strength
+
Thermal Radio Contribution

Observational Information

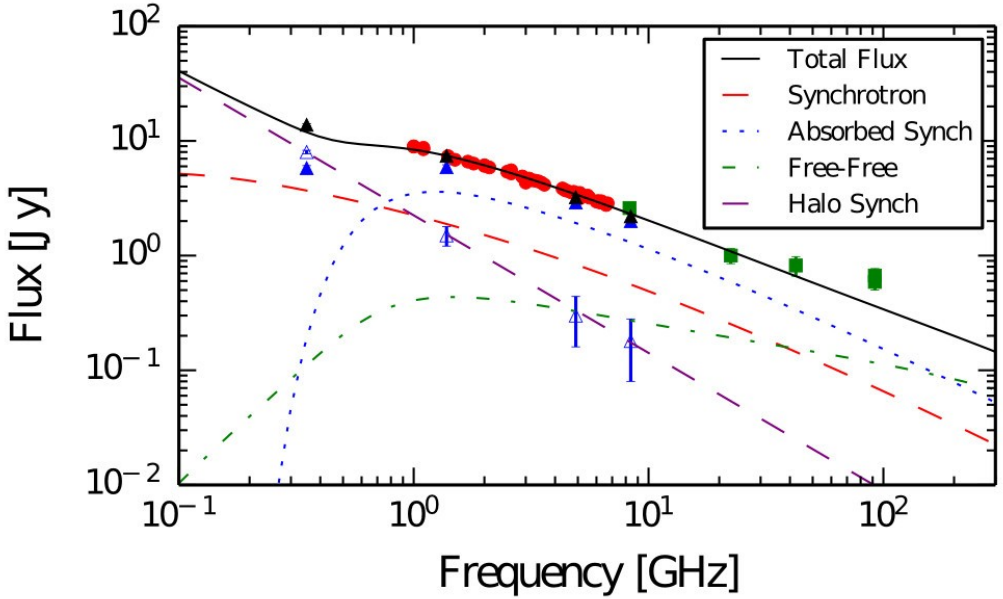
- Radio
  - Supernova rate
- Millimeter
  - Molecular gas content
- Infrared
  - Radiation field
  - Dust temperatures
- Optical
  - ISM pressures, wind
- X-Rays
  - Hot gas content, wind

M82 Core – Radio Continuum



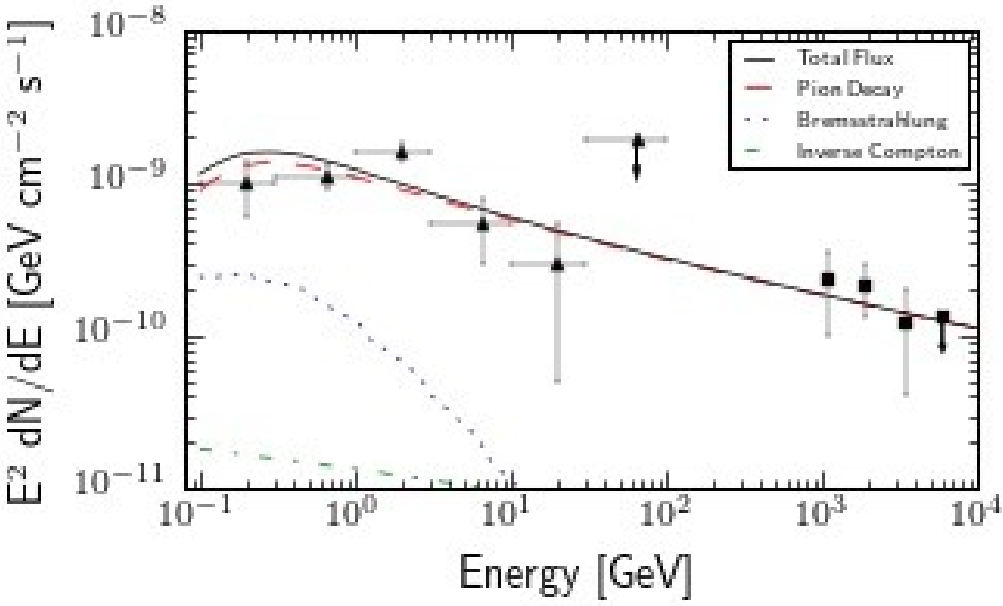
Muxlow+ 1995, L-Band MERLIN Image

M82 Radio & Gamma-Ray Spectral Fits



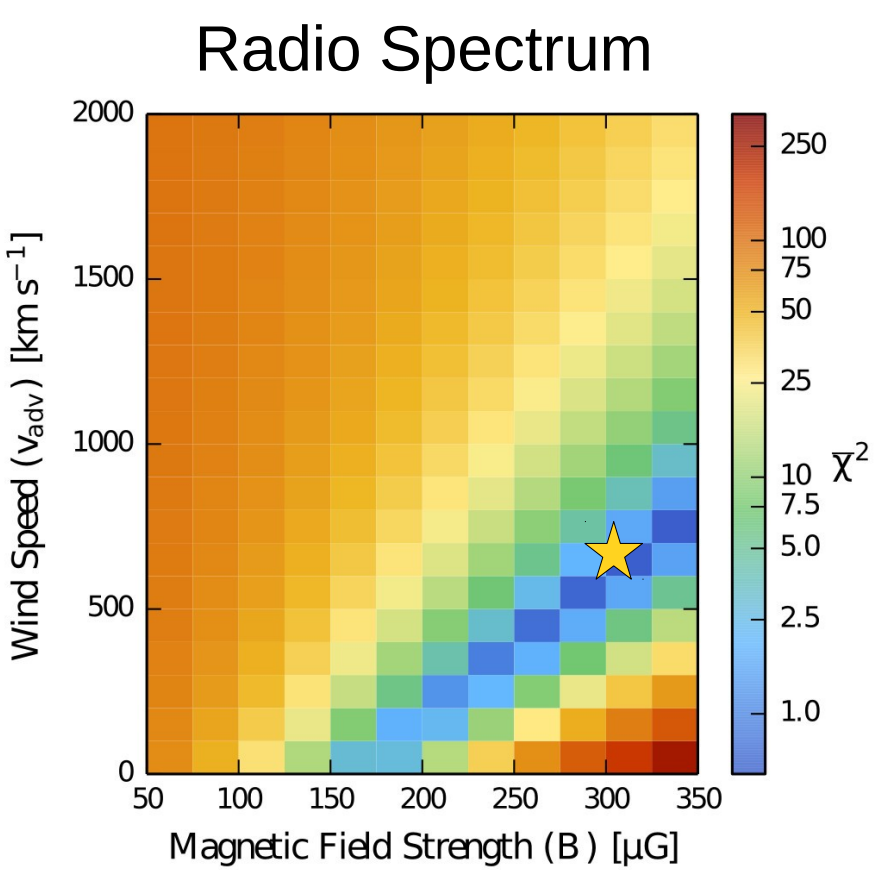
Radio spectrum contains both synchrotron and free-free emission with free-free absorption at low-frequencies.

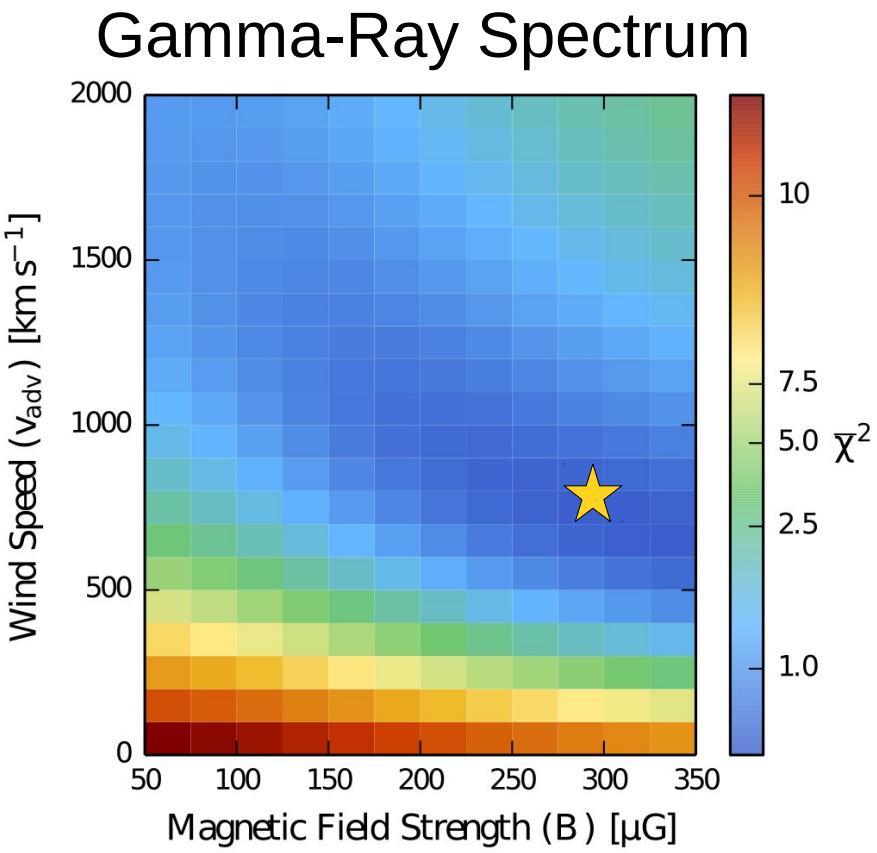
Gamma-ray emission is mainly from neutral pion decay, but also includes bremsstrahlung.



Yoast-Hull+ 2013, ApJ, 768

Chi-Squared Tests: Galactic Wind



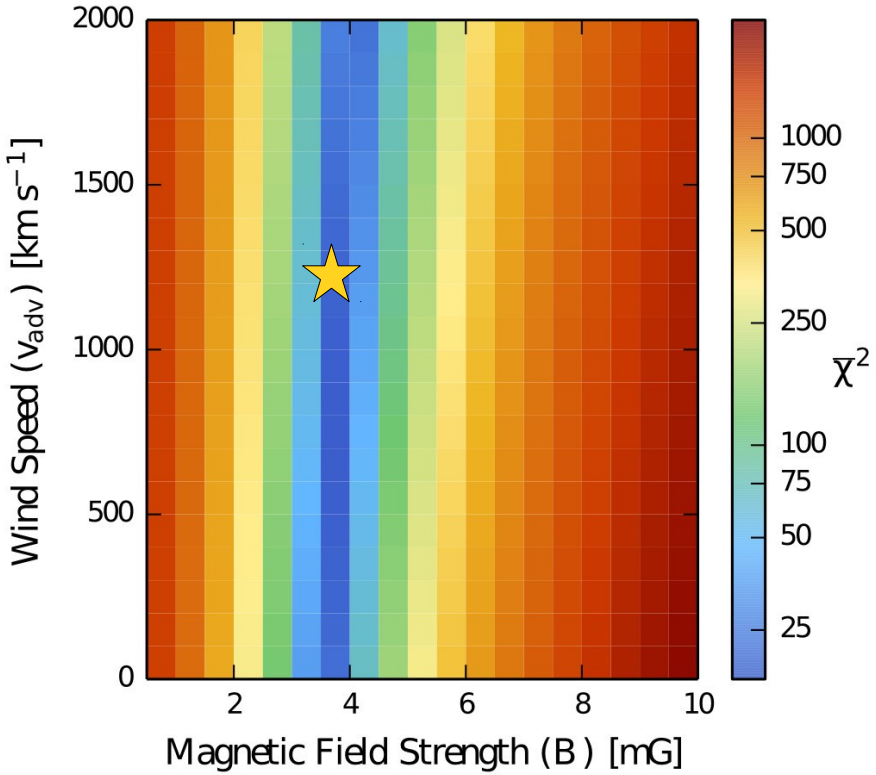


We use chi-squared tests to optimize magnetic field strength (B), wind speed (v_{adv}), ionized gas density (n_{ion}).

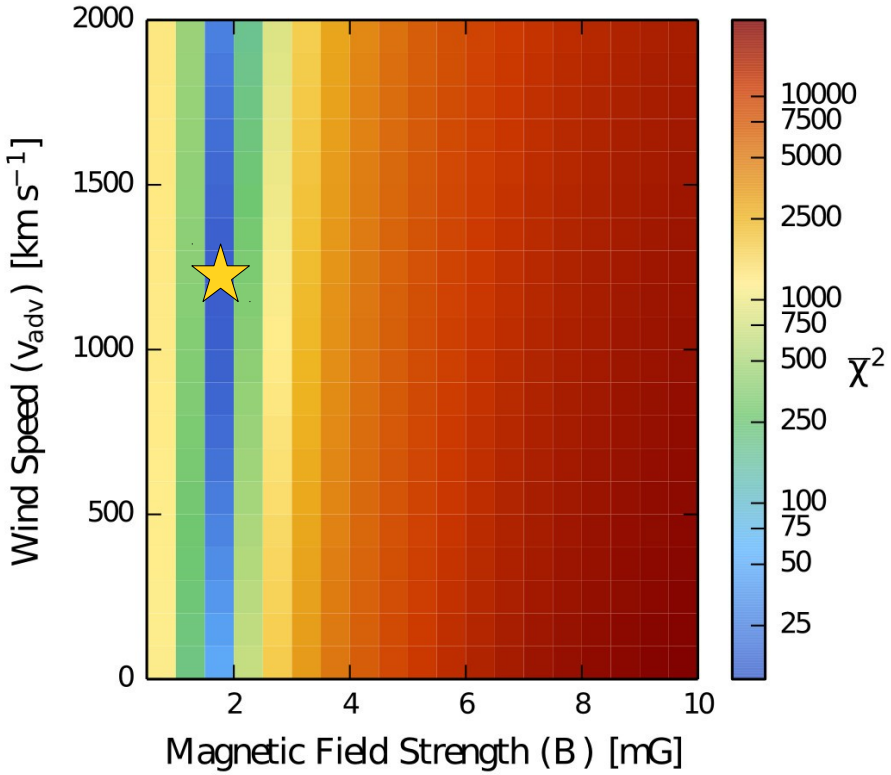
Yoast-Hull+ 2013, ApJ, 768

Proton Calorimetry in Arp 220

Eastern Nucleus



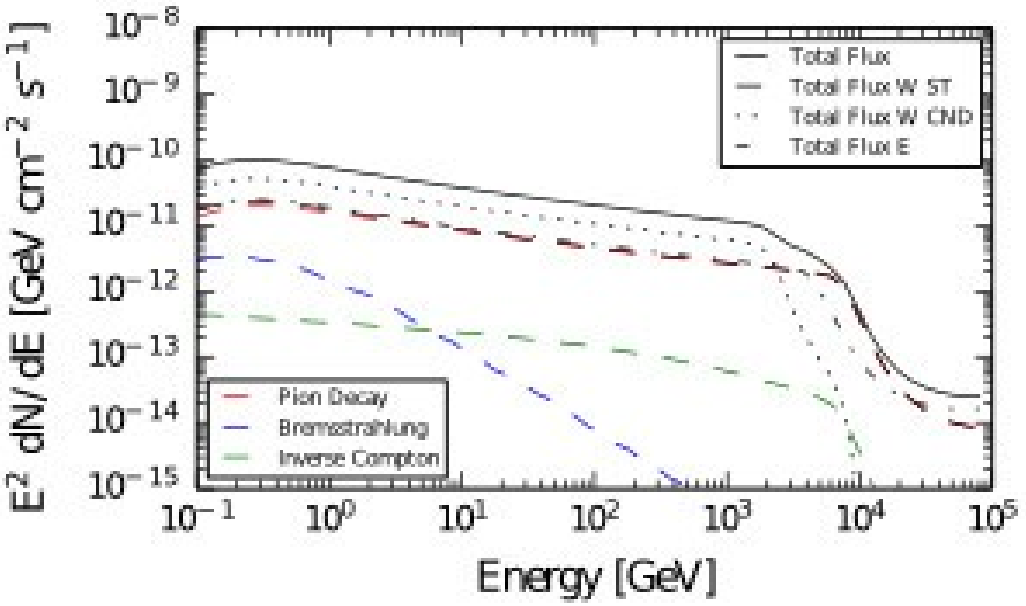
Western Nucleus



In the calorimeter limit, wind speed does not affect the total cosmic ray electron population. Thus, the gamma-ray spectrum can be reliably predicted with only an observed radio spectrum and star formation rate.

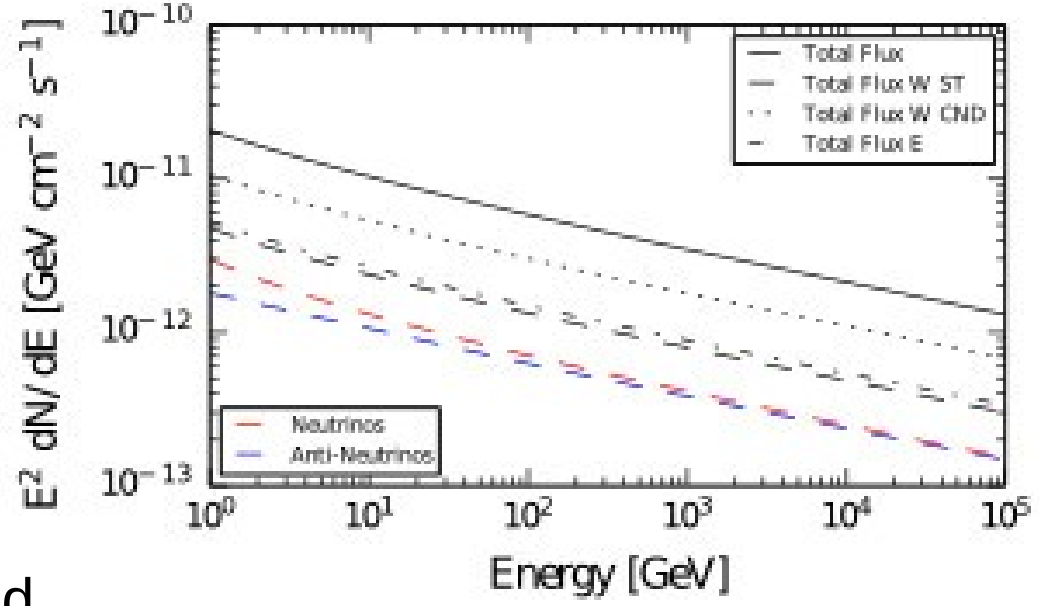
Yoast-Hull+ 2015, MNRAS, submitted

Arp 220: Predicted Spectra



Arp 220 is likely detectable at GeV energies by *Fermi*, but not above ~10 TeV due to gamma-gamma absorption.

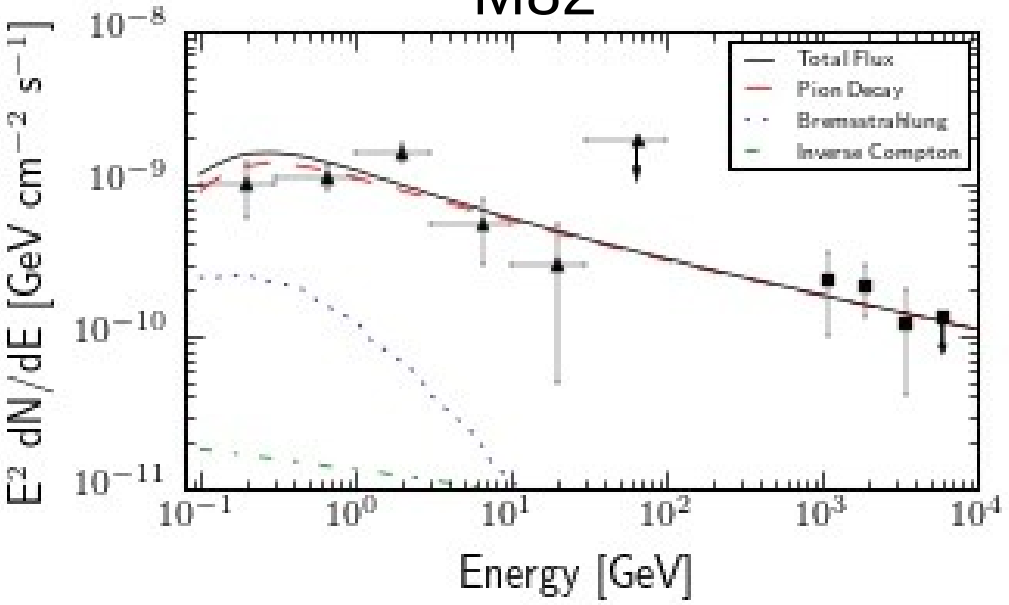
TeV gamma-rays are not a reliable indicator of neutrino fluxes due to gamma-gamma absorption.



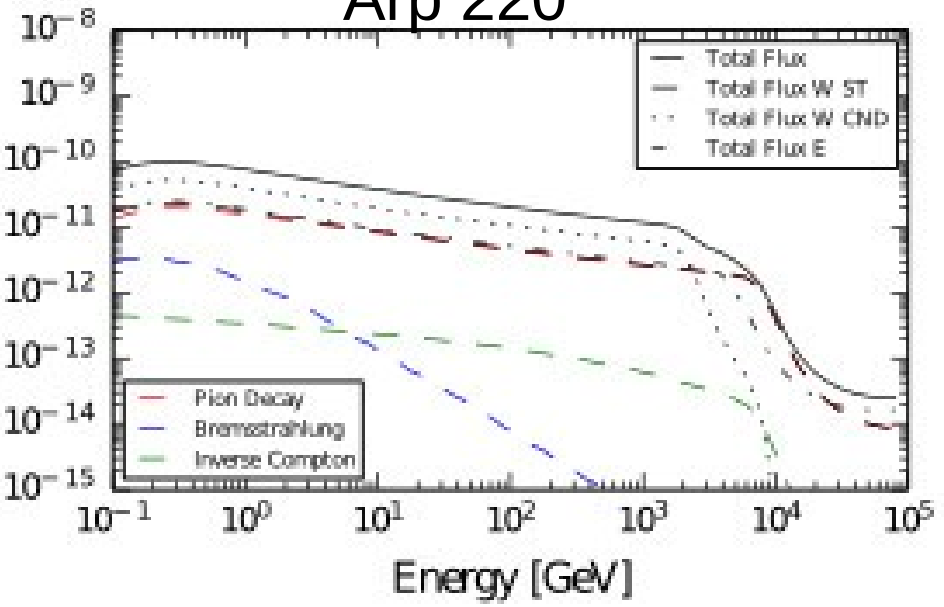
Yoast-Hull+ 2015, MNRAS, submitted

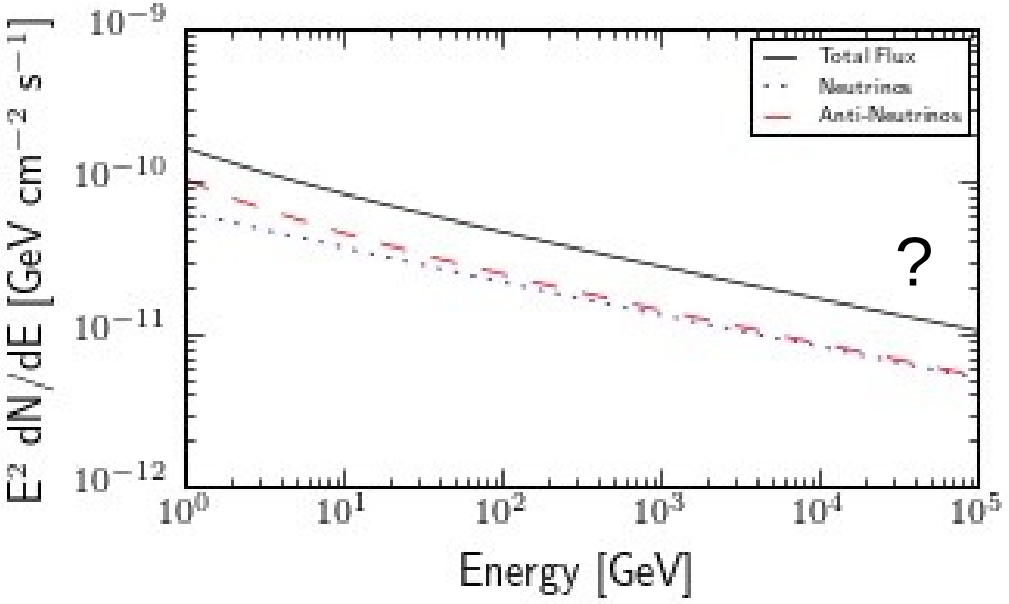
Gamma-Ray & Neutrino Spectra

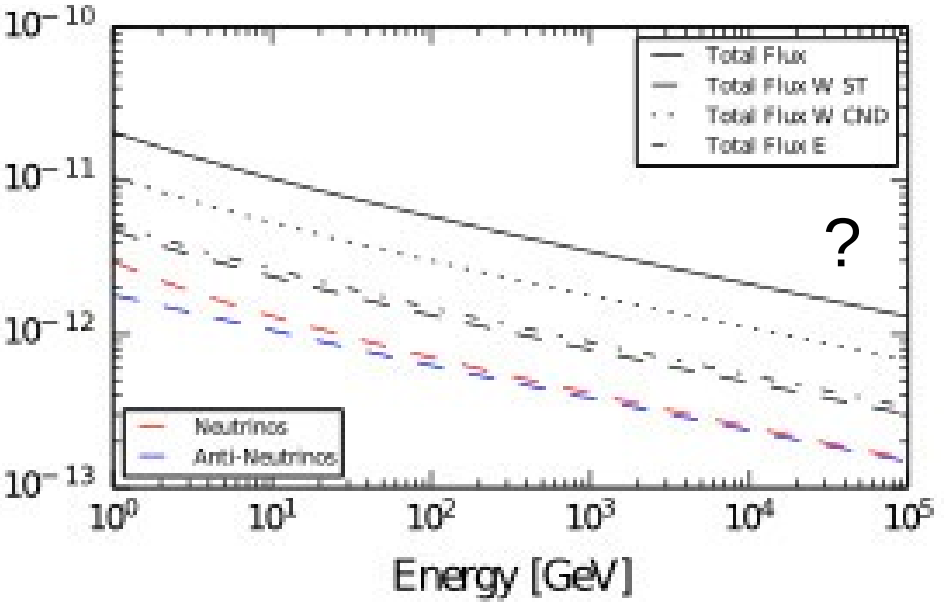
M82



Arp 220







High Energy Sources

- Starburst galaxies are unlikely to be detected as point sources in neutrinos.
  - Proton calorimetery is not applicable to all starbursts.
  - Highest energy CRs are not necessary to model radio & gamma-ray spectra.
- Can starbursts alone provide an isotropic HE neutrino flux?
  - Roughly 10% of all starburst galaxies harbor AGN.
- Are the sources of cosmic rays, gamma-rays, and cosmic high-energy neutrinos the same?