Cosmic Rays & Multi-Messenger Opportunities in Starbursts

Tova M. Yoast-Hull
Canadian Institute for Theoretical Astrophysics

RAPP Center Inauguration, Ruhr-Universität Bochum
22 September 2016

CITA–ICAT

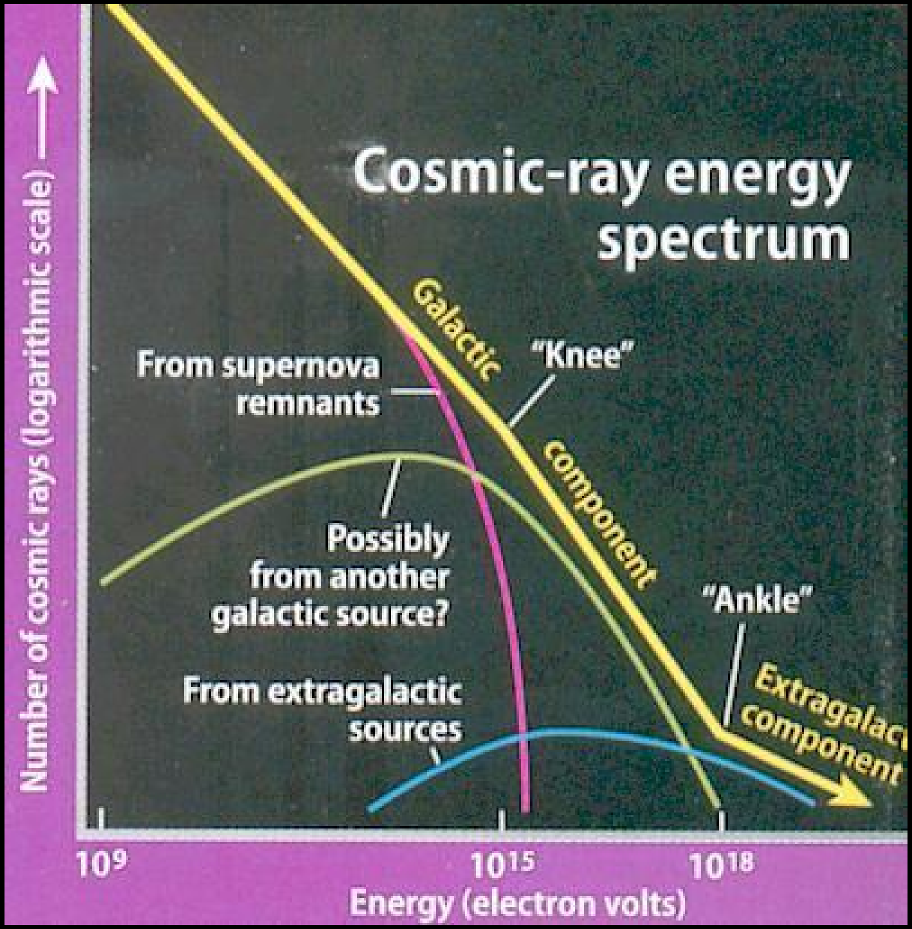
In This Talk ...

- Why Starburst Galaxies?
- Modeling Cosmic Rays
  - Radio, Gamma-Rays, & Neutrinos
- Lessons from Starbursts
  - Cosmic Ray Connections to Galaxy Evolution

I. What's Up With Starburst Galaxies

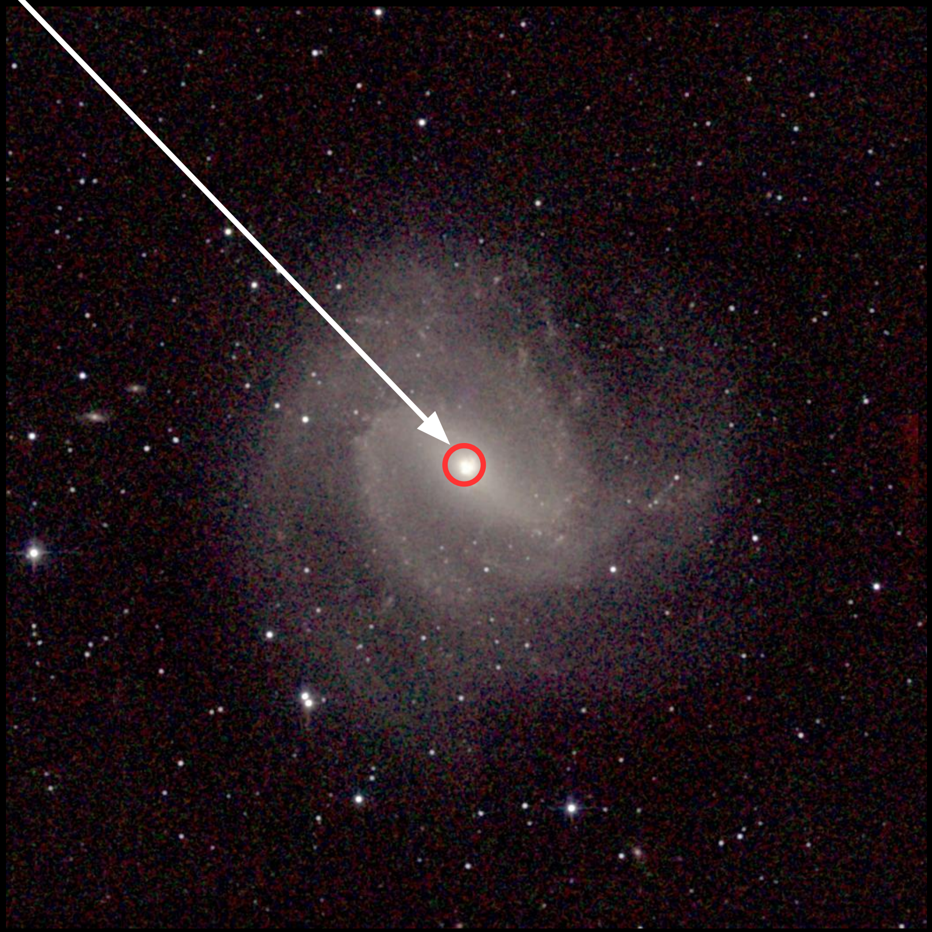
High Energy Cosmic Rays

- What are the sources of high energy cosmic rays?
- Where are astrophysical neutrinos being produced?
- How does environment affect cosmic ray populations?



Central Molecular Zones

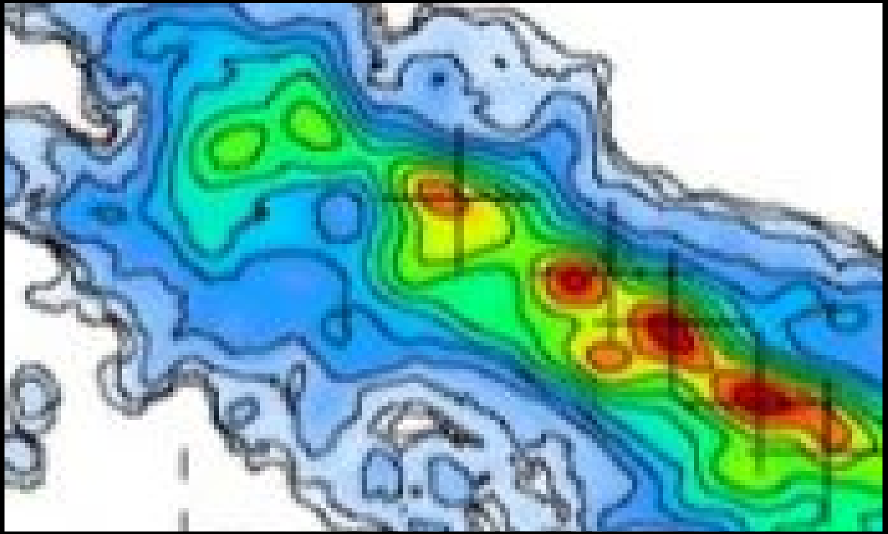
- CMZs in starburst galaxies are characterized by:
  - Radius ~ 100 to 300 pc
  - Large amounts of dense molecular gas
  - Strong magnetic fields and intense radiation fields
  - High and highly variable star-formation rates



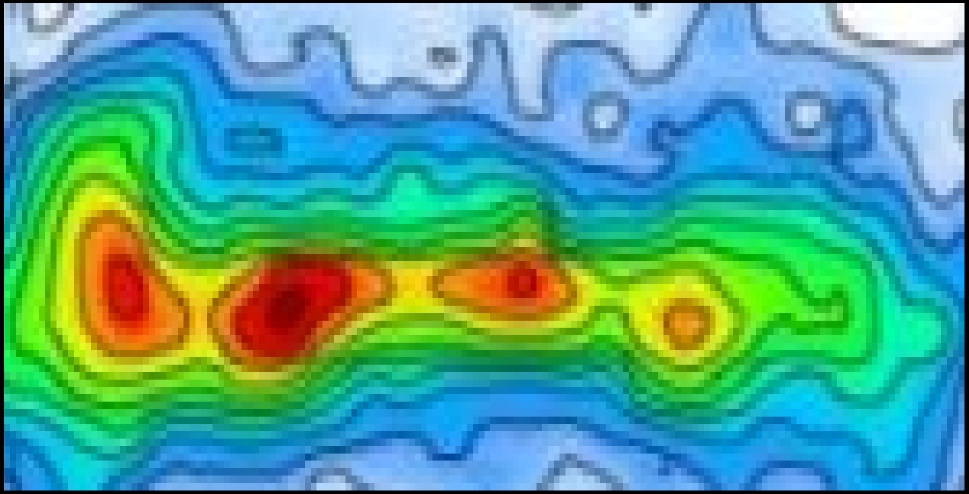
Nuclear Starburst Galaxy: M83

Star Formation in CMZs

- Kennicutt-Schmidt correlation breaks down in CMZs
  - SFR in Galactic Center is down by factor of ~10 from predicted
- Many nearby starbursts with similar gas densities and SFRs
  - Only a couple detected in gamma-rays

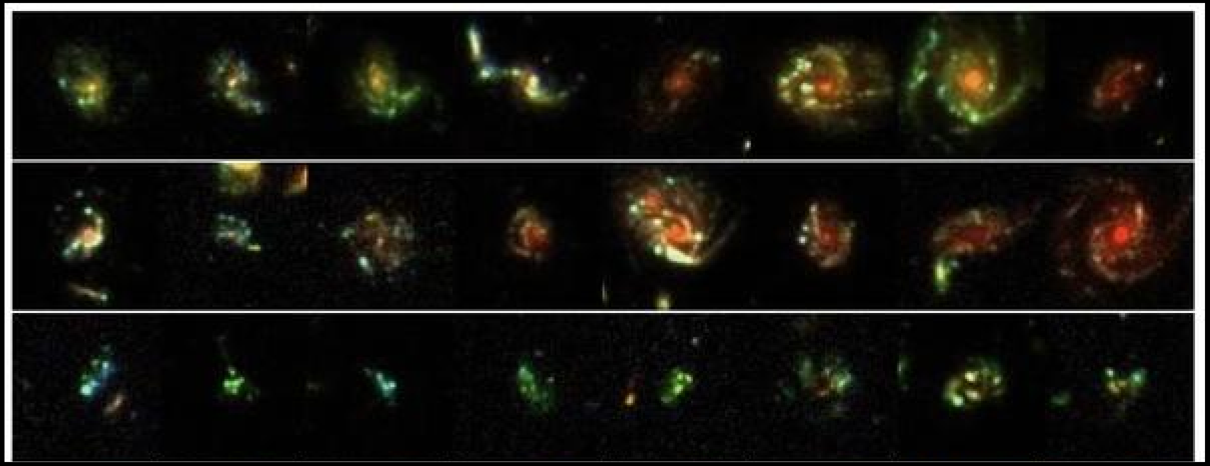


Starburst Galaxy: NGC 253

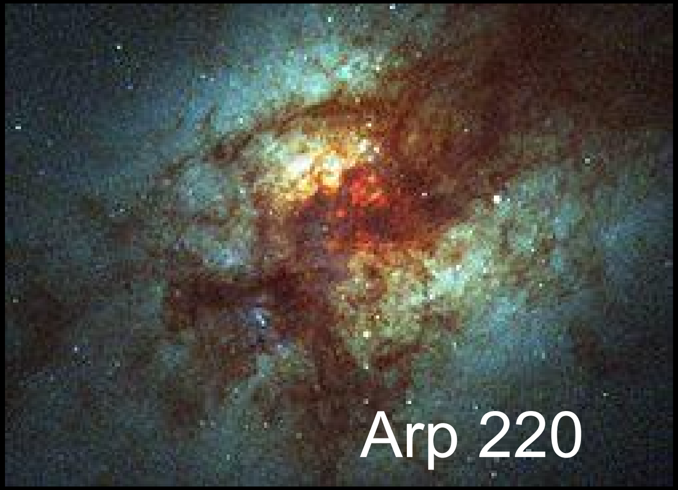


Galactic Center

High Redshift Analogues

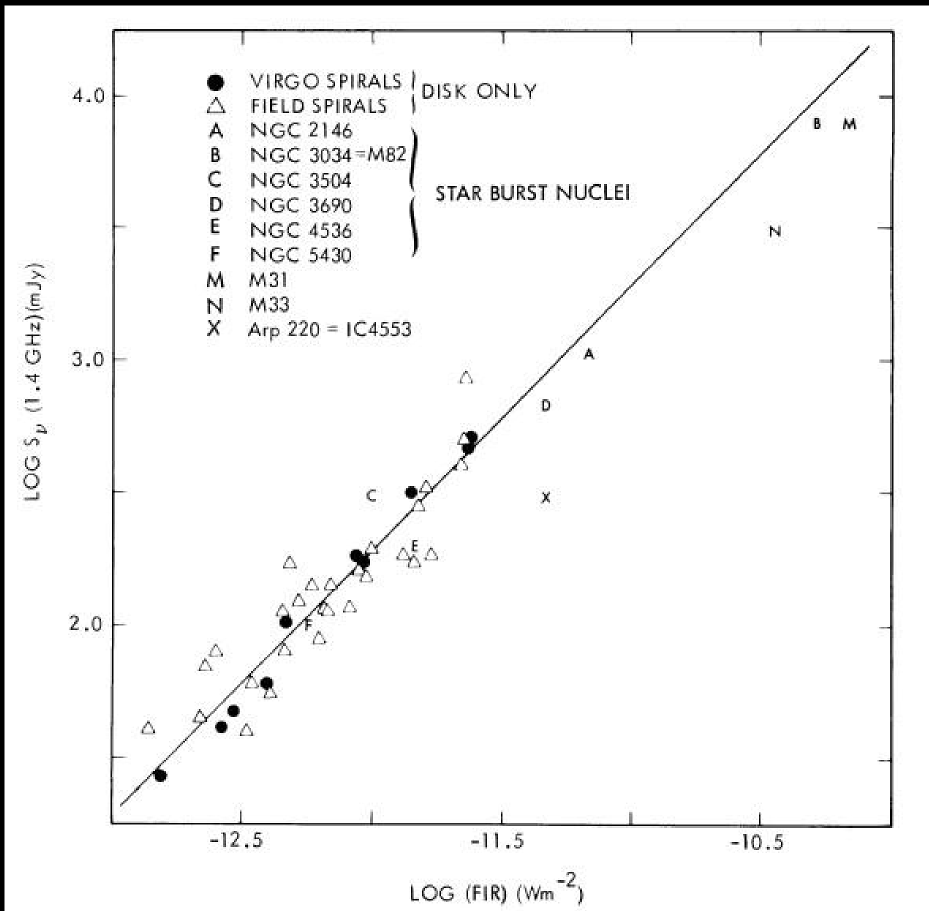


- Star formation at in high redshift galaxies is very clumpy.
  - Can study nearby galaxies to learn about similar environments.



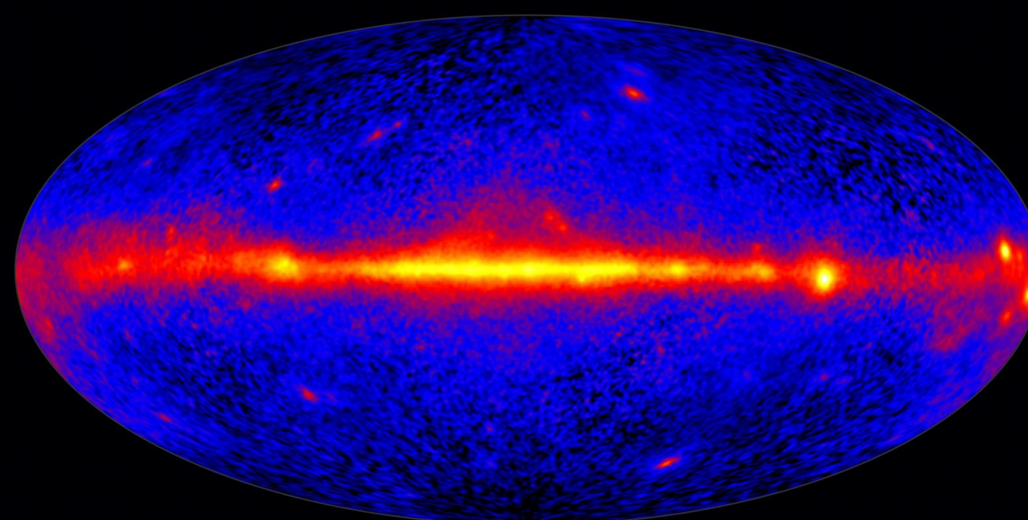
II. A History of Cosmic Ray Models

1980s & 1990s: New Discoveries



Helou+ 1985, ApJL, 298

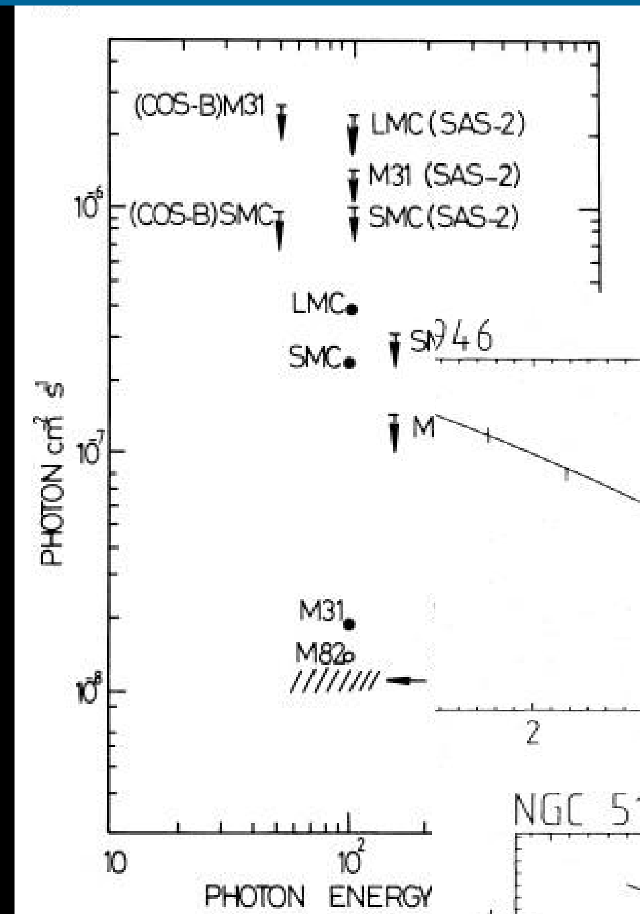
- First investigations into the far-infrared – radio correlation (de Jong+ 1985, Helou+ 1985)
- EGRET launches in 1991



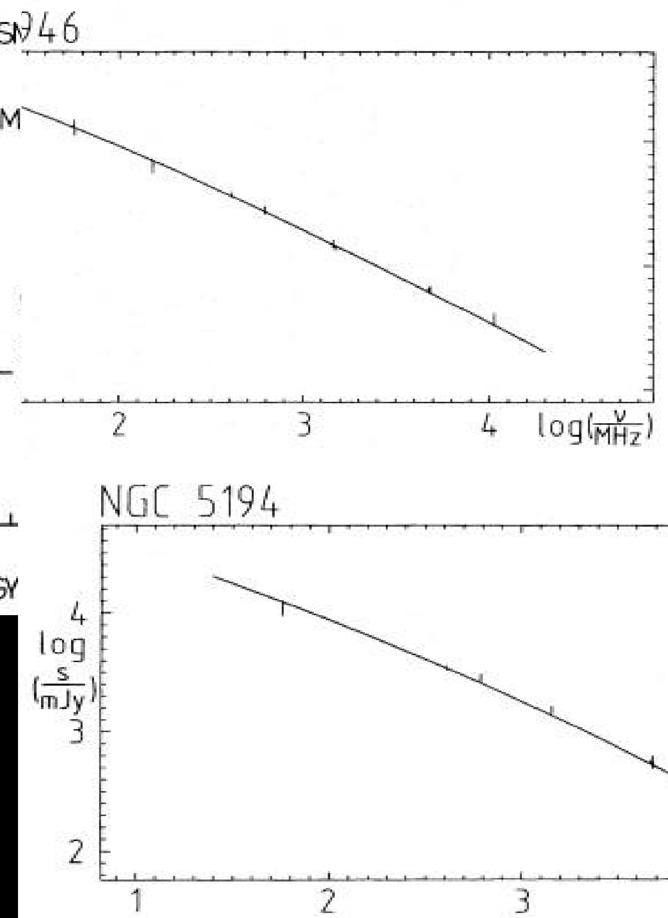
EGRET all-sky map of gamma rays above 100 MeV

Early Cosmic Ray Models

- Late 1980s:
  - FIR-radio correlation
  - New radio observations of starbursts
  - Minimum energy magnetic field estimates
- Early 1990s:
  - CR propagation models connected to radio emission from starbursts
  - Predictions for detection of M82 with EGRET in gamma-rays

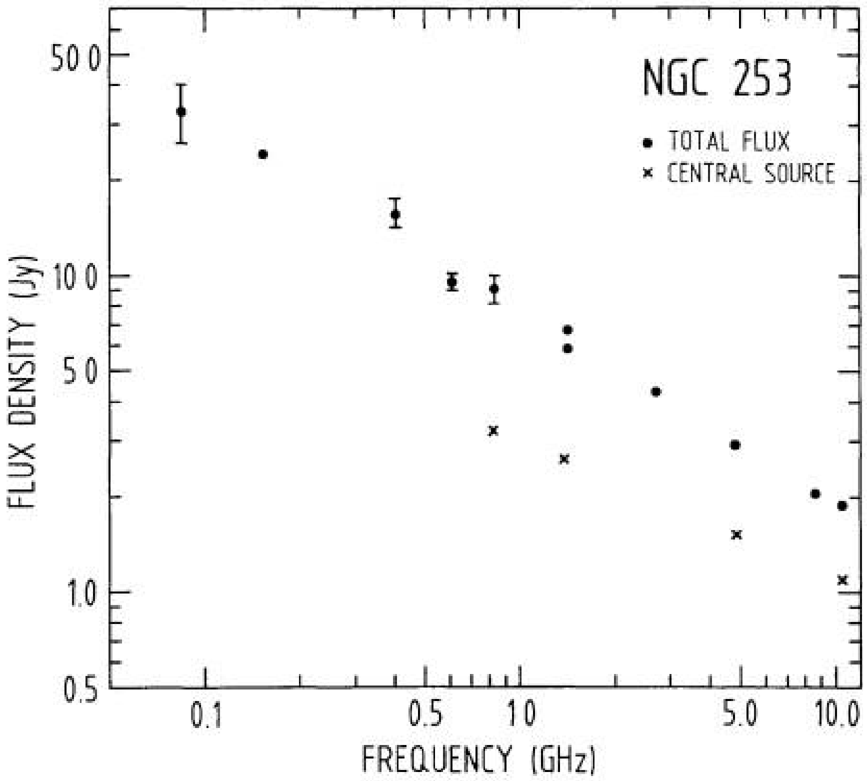


Pohl+ 1991, A&A, 250



Akyüz+ 1991, A&A, 248

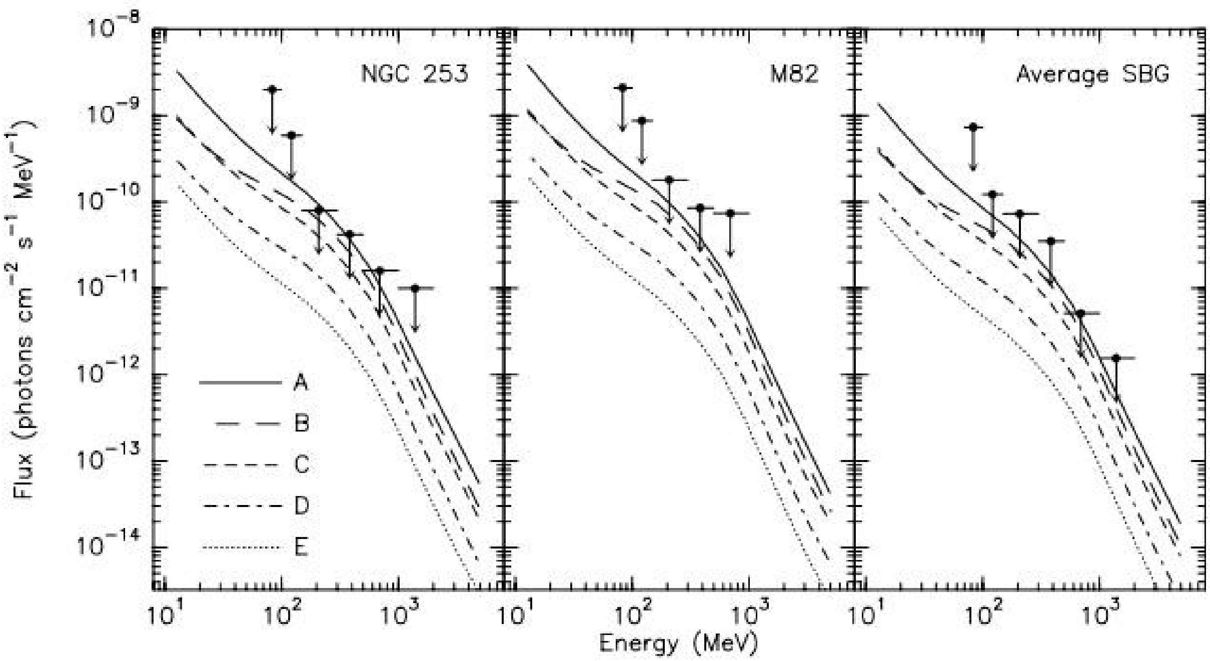
Early Multiwavelength Observations



Hummel+ 1984, A&A, 137

- Radio observations of CMZs
- Gamma-ray upper-limits from EGRET.

Blom+ 1999, ApJ, 516



Basics of Cosmic Ray Models

- CR transport equation:

$$\frac{N(E)}{\tau(E)}-\frac{d}{dE}[b(E)N(E)]-Q(E)=0$$

- CR source function:

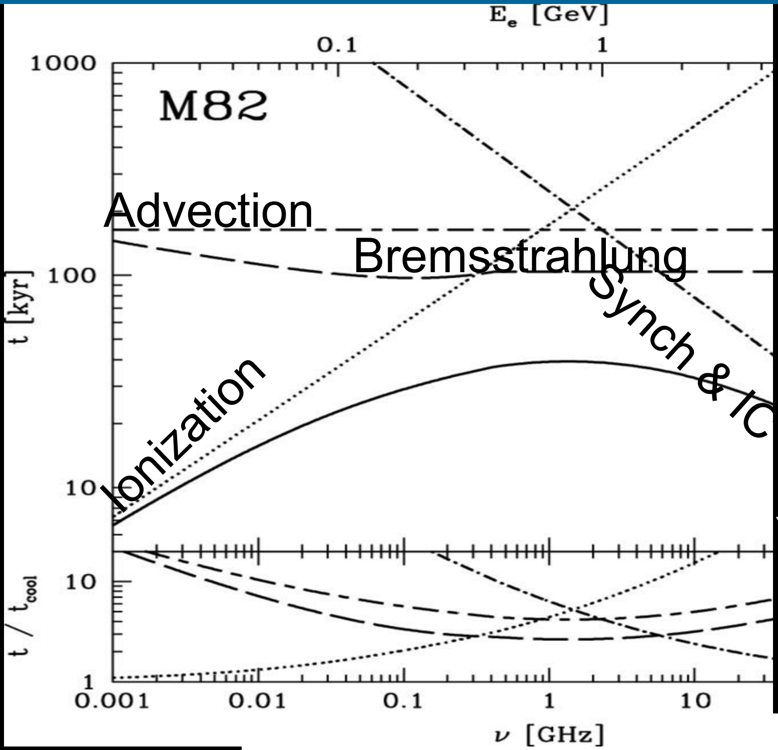
$$\int Q(E)E\,dE=\frac{\eta\nu_{SNR}E_{51}}{V}$$

- CR lifetimes:

$$\tau^{-1}=\tau_{diff}^{-1}+\tau_{adv}^{-1}+\tau_{loss}^{-1}$$

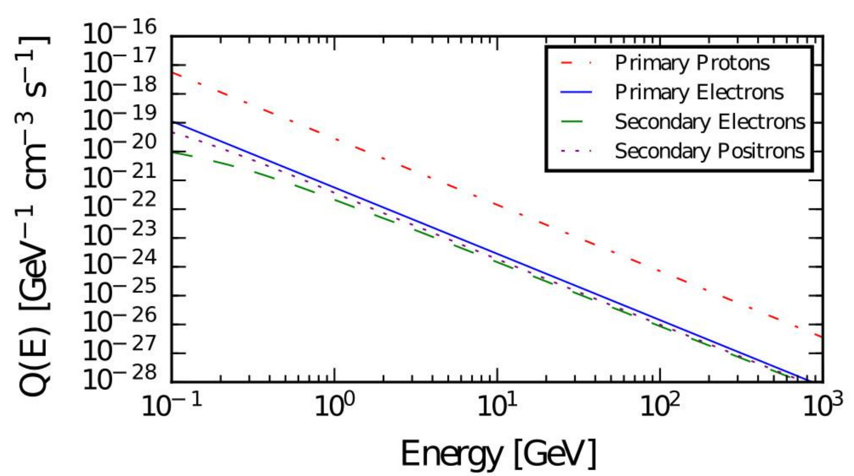
- Secondary CRs / γ-rays, ν:

$$q(E)\propto\int\frac{d\sigma(E,E_p)}{dE_p}N_p(E_p)dE_p$$

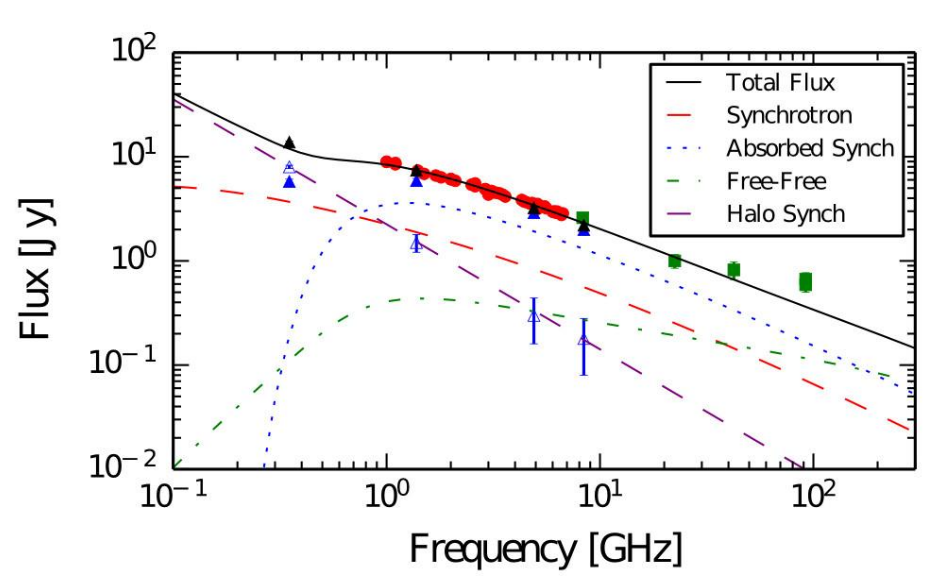


Lacki+ 2013, MNRAS, 430

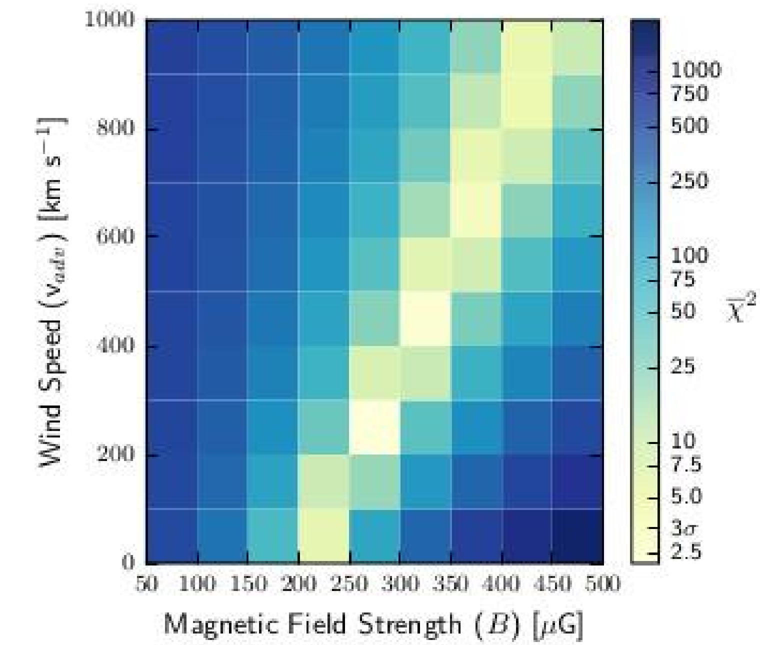
Yoast-Hull+ 2013, ApJ, 768

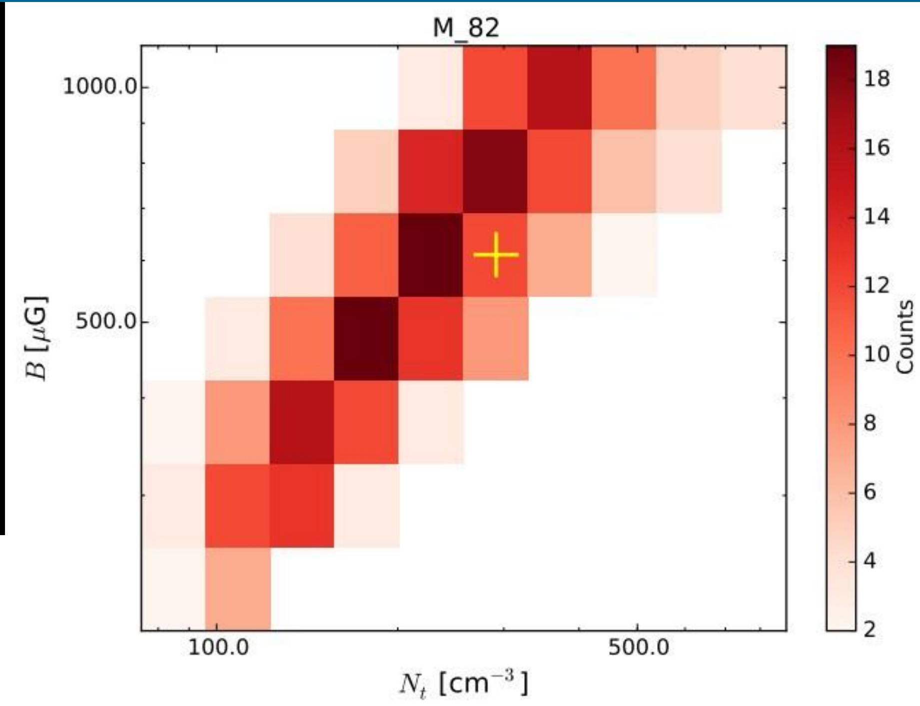


Cosmic Rays & Radio in M82



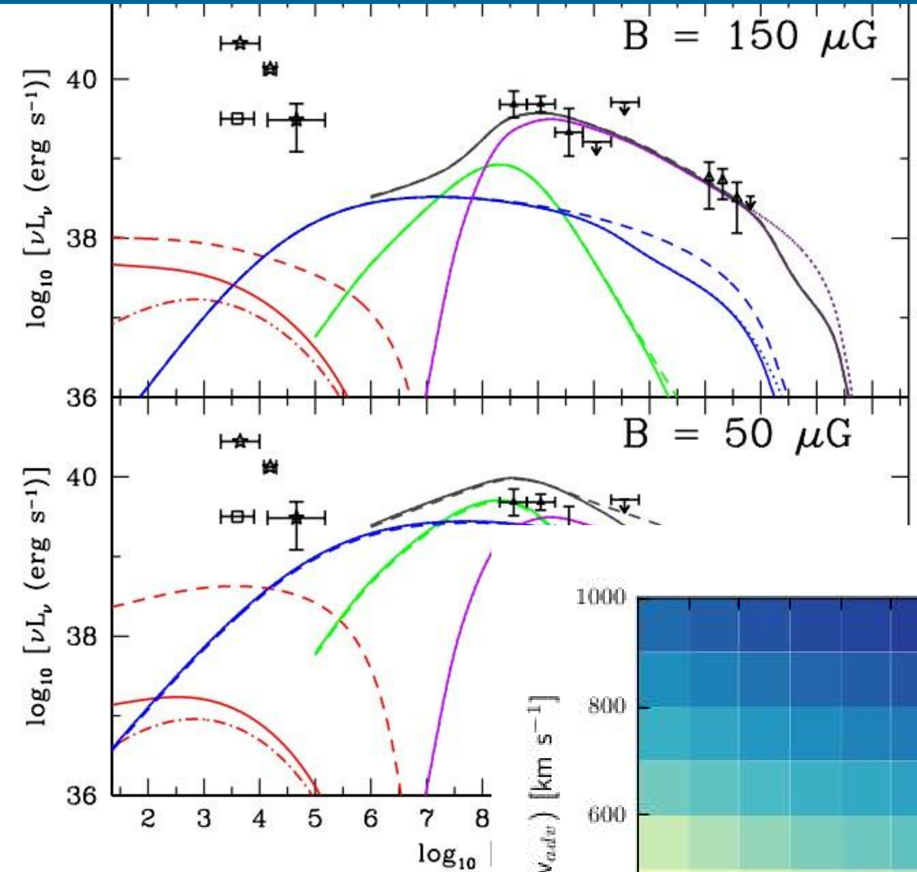
Yoast-Hull+
2013, 2015



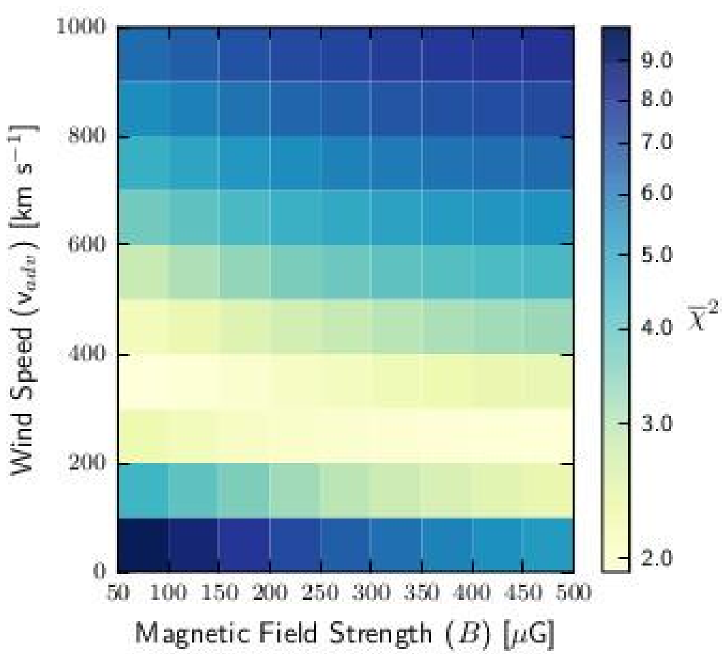


Eichmann & Tjus,
2016, ApJ, 821

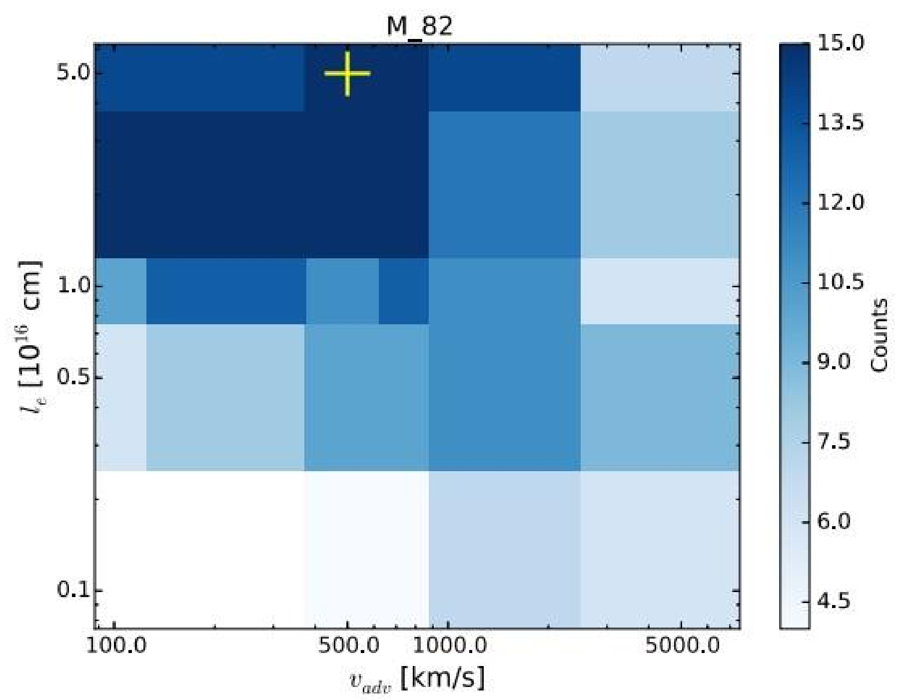
Cosmic Rays & Gamma-Rays in M82



Lacki & Thompson, 2012, ApJ, 762

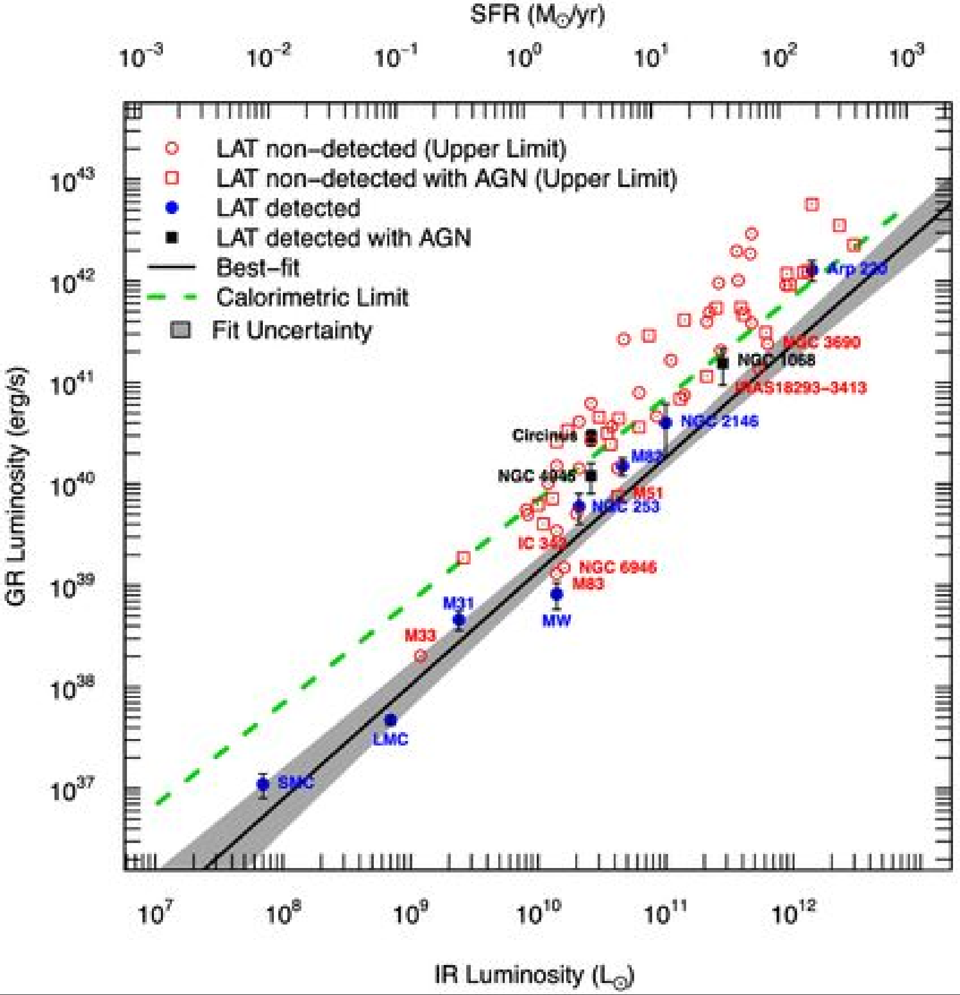


Yoast-Hull+ 2013, 2015



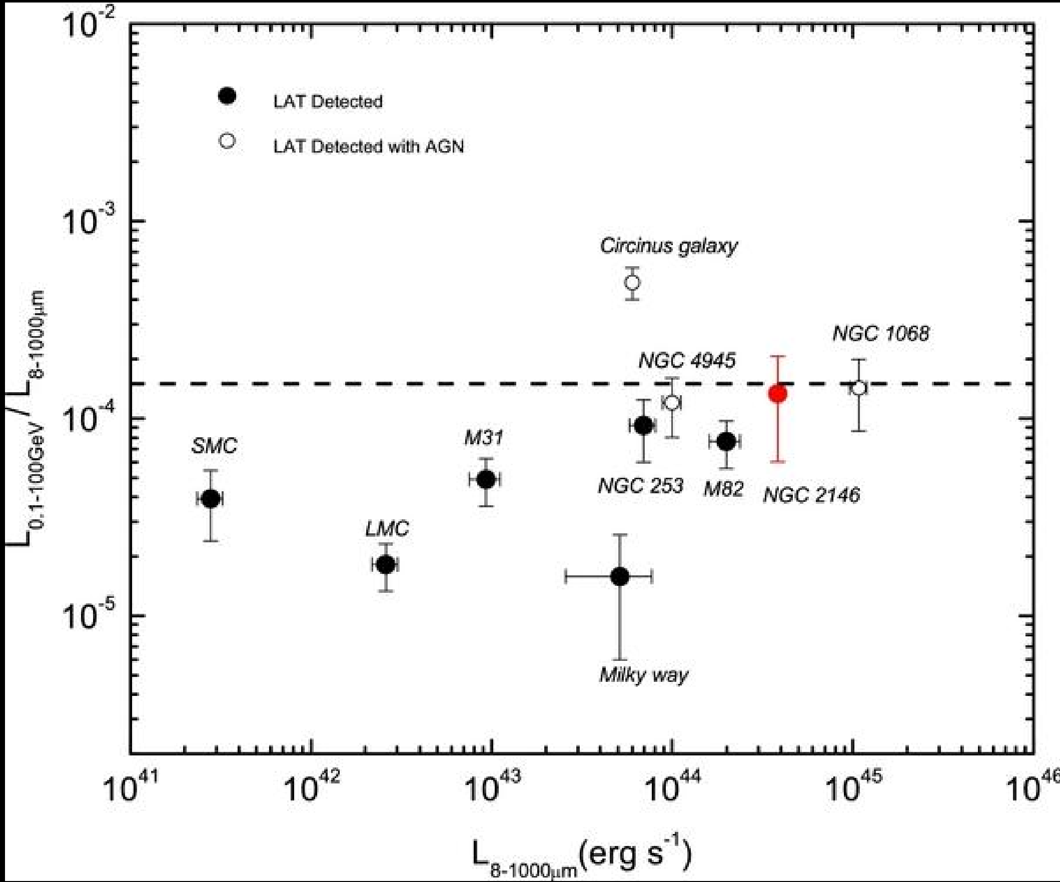
Eichmann & Tjus, 2016, ApJ, 821

FIR – Gamma-Ray Correlation

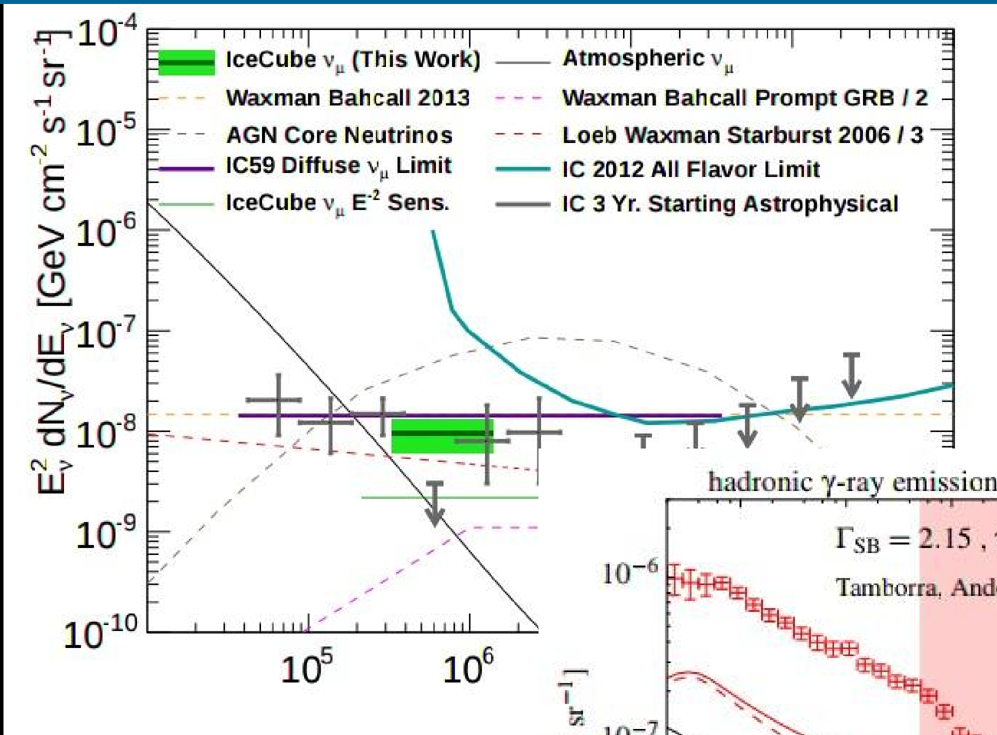


Rojas-Bravo & Araya 2016, MNRAS, 463

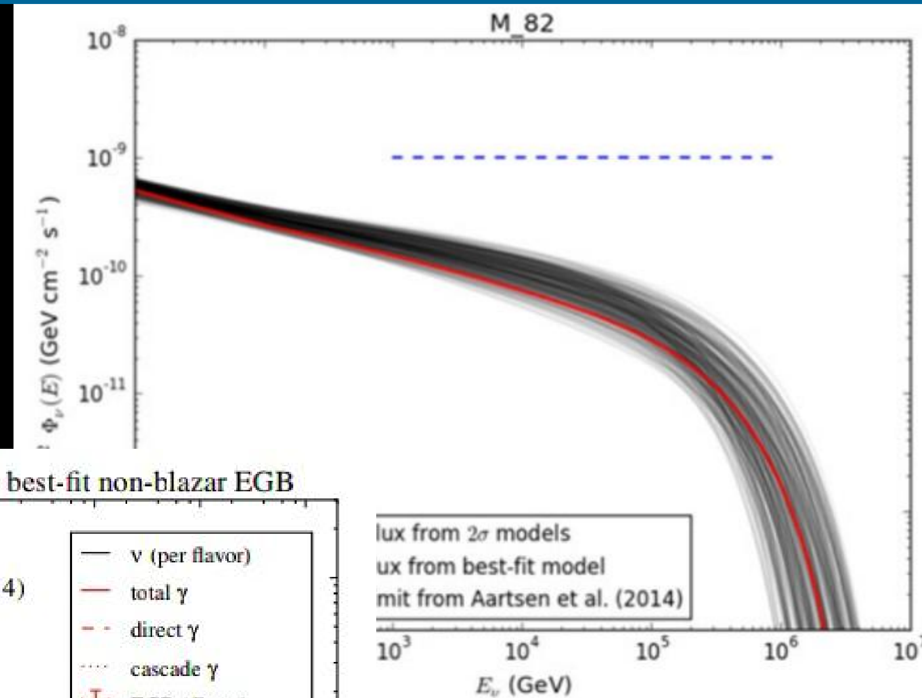
Tang+ 2015, ApJ, 794



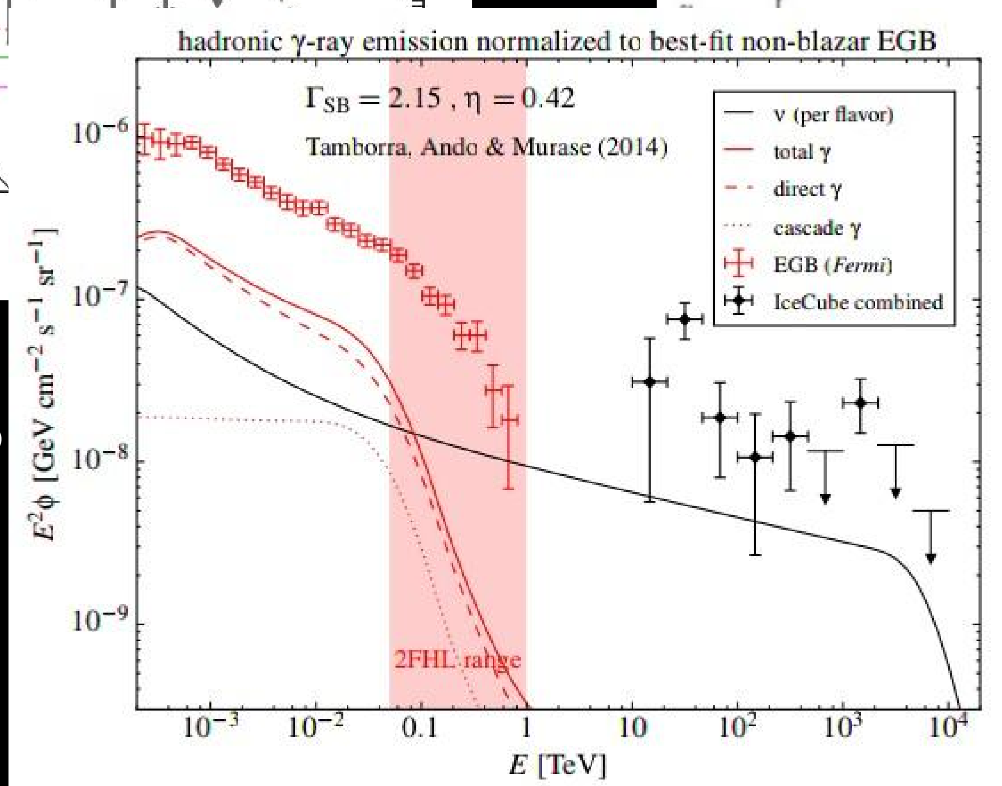
Cosmic Rays & Neutrinos



Waxman 2015,
arXiv 1511.00815



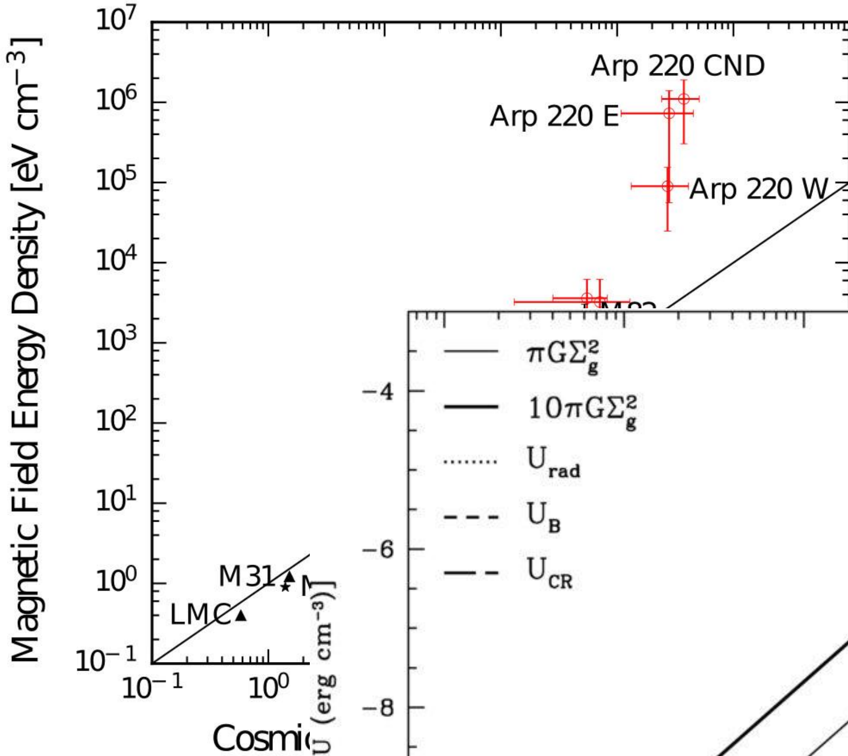
Eichmann & Tjus,
2016, ApJ, 821

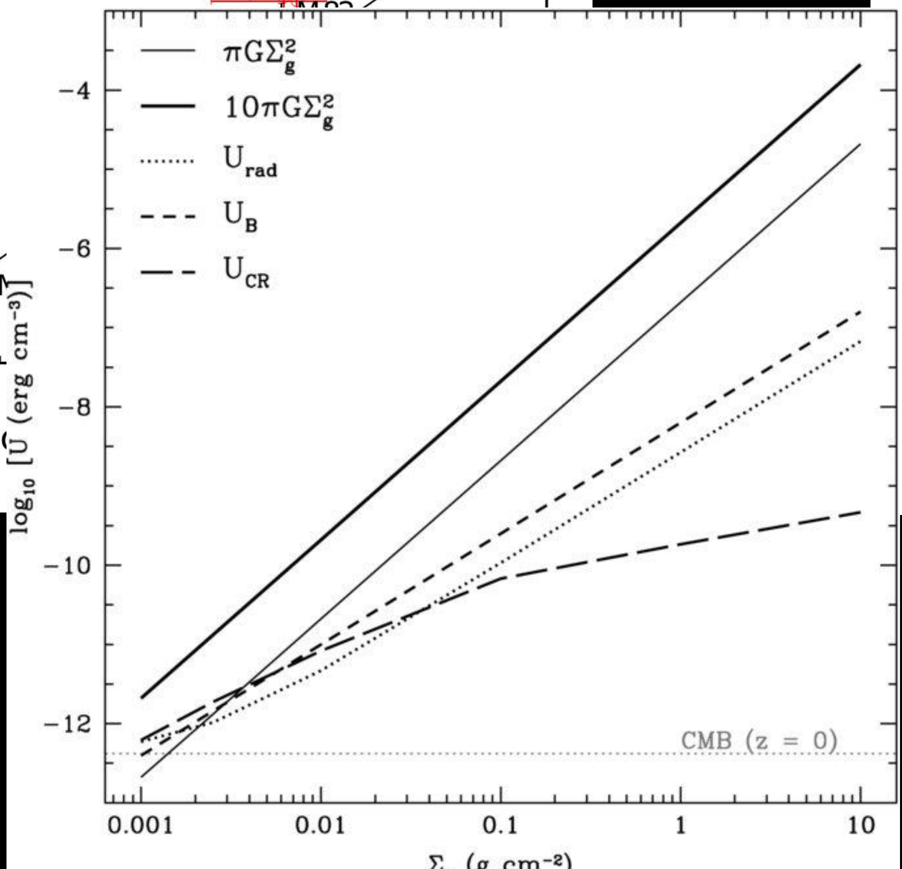


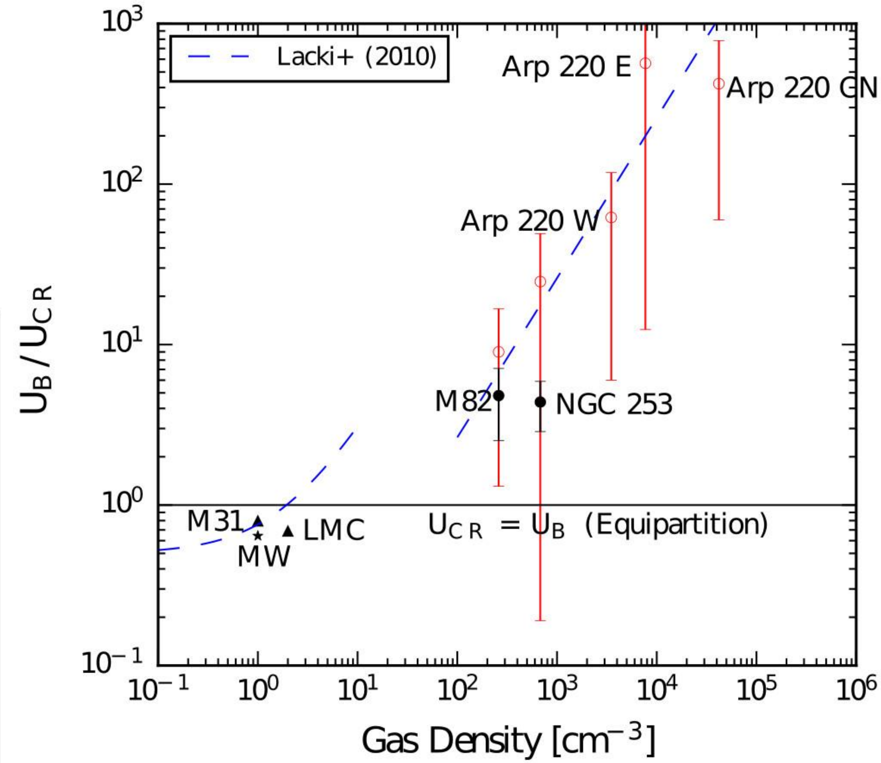
Bechtol+ 2015,
arXiv 1511.00688

III. A Window into Galaxy Evolution

Energy Densities in CMZs





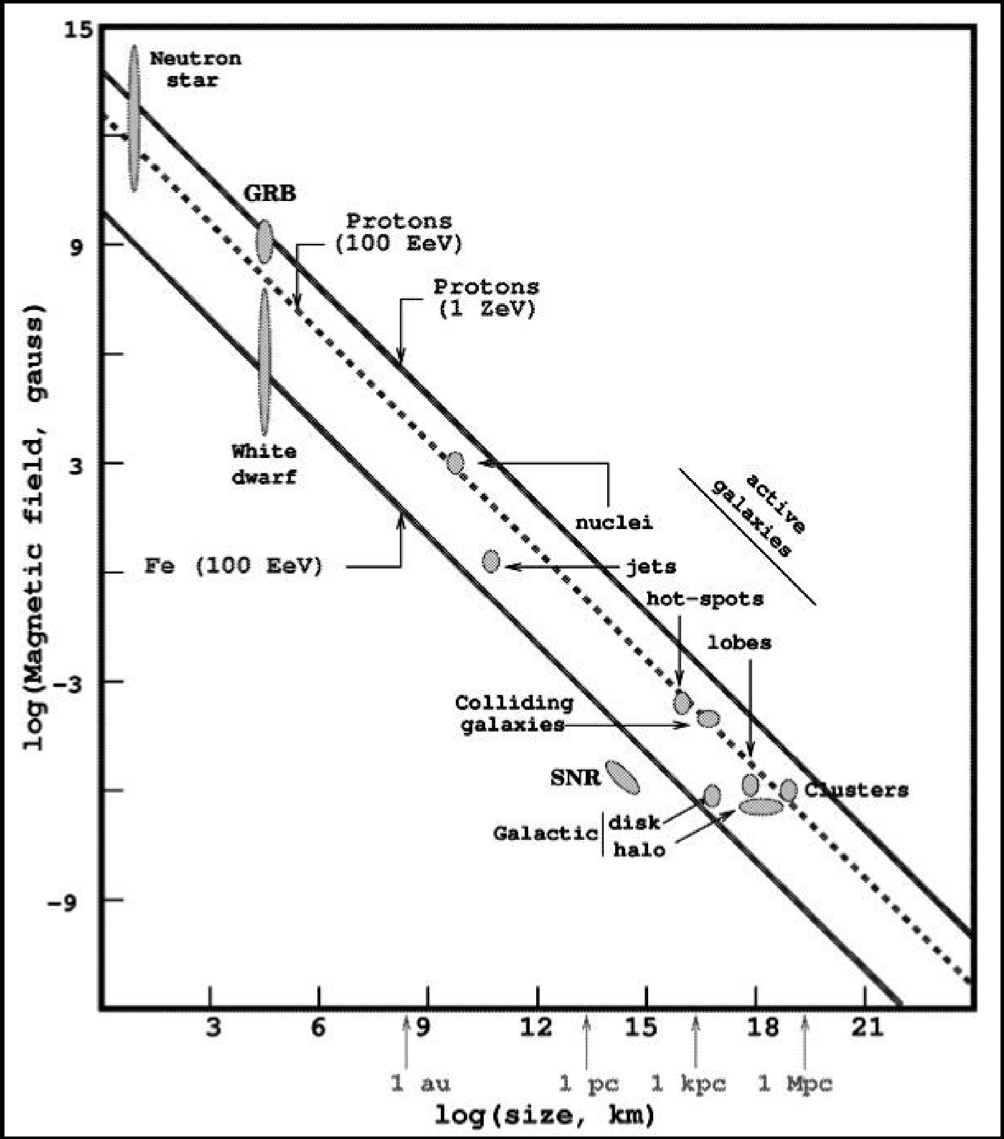


Yoast-Hull+ 2016, MNRAS, 457, L29

Lacki+ 2010, ApJ, 717, 1

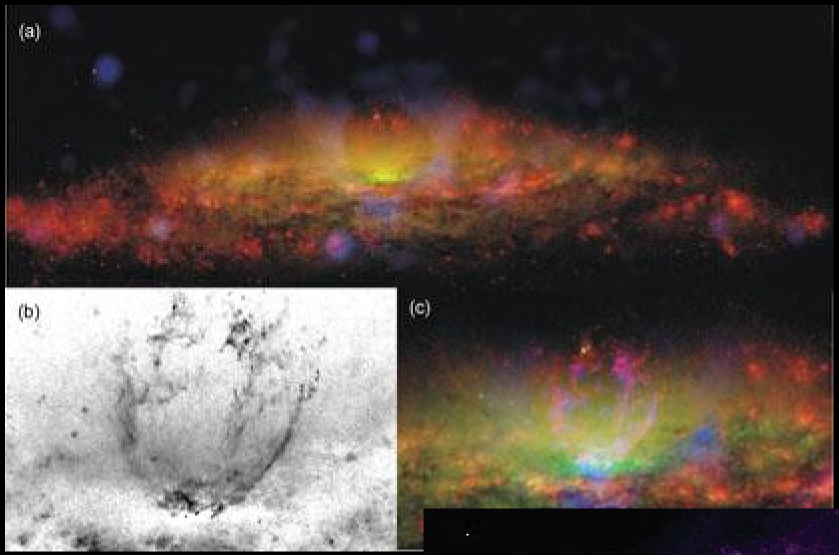
Very High Energy Cosmic Rays

- SNRs in our Galaxy accelerate CRs up to $\sim 10^{14}$ eV energies.
- Magnetic fields in starbursts range from ~ 100 μG to ~10 mG.

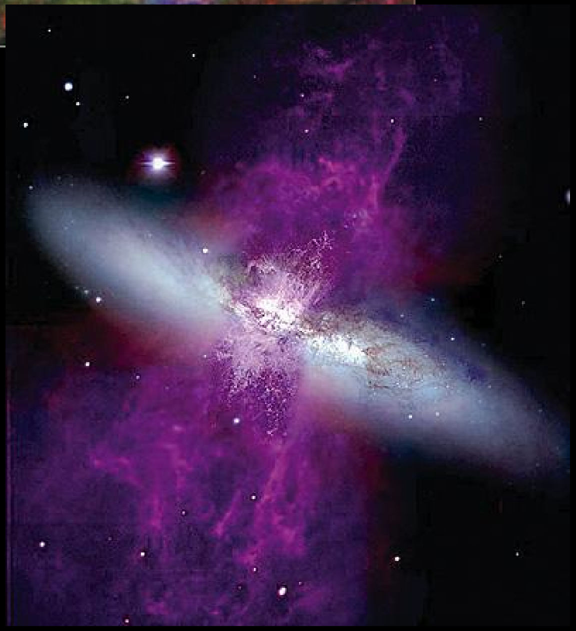


Cosmic Rays & Feedback

- Galactic Feedback:
    - ISM heating by cosmic rays
    - Cosmic ray driven winds
- FIR-Radio Correlation



NGC 3079



M82

Summary

- Starburst Galaxies:
  - Sites of intense star-formation and high rates of cosmic ray interactions.
  - Potentially sources of very high energy to ultra high energy CRs and astrophysical neutrinos.
- Radio + Gamma-Rays:
  - Combination of these observations are very powerful in constraining CR & ISM properties.
  - Many new telescopes (CTA, SKA) will be important for CR studies.
- Galaxy Evolution:
  - Nearby galaxy examples demonstrate impact of CRs on ISM & IGM; useful for high redshift studies.