The Multiwavelength Properties of Arp 220

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8 August 2017

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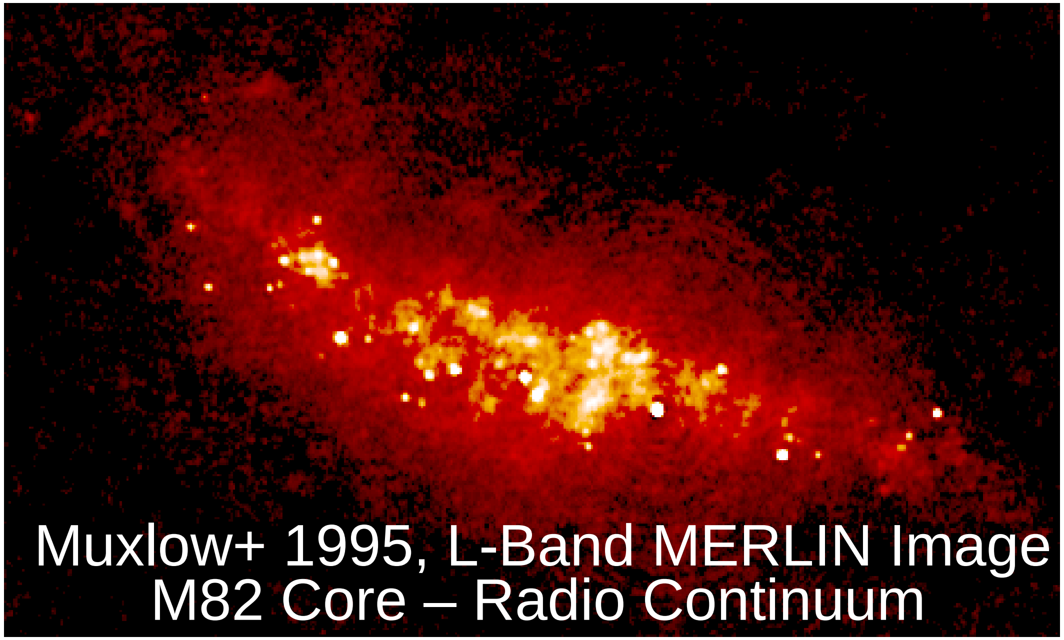
In This Talk ...

- The Interstellar Medium of Arp 220
- Non-Thermal Detections
- Radio & Gamma-Ray Disconnect

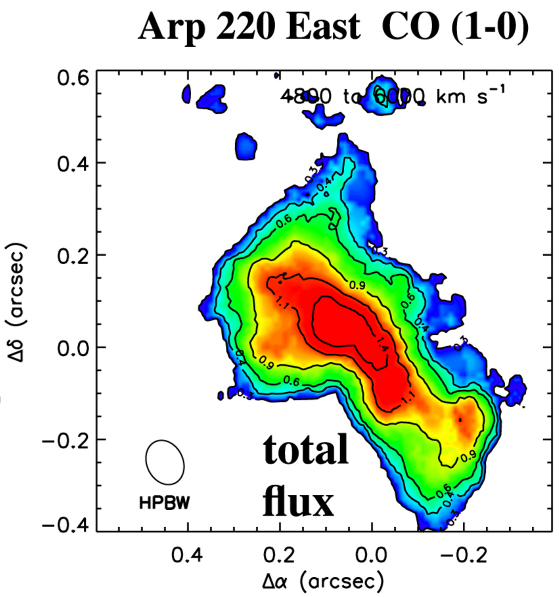
Observational Information

- 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

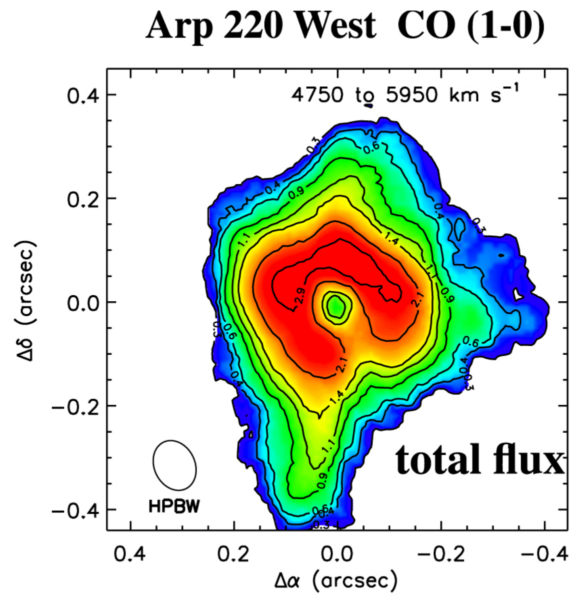


Essential Properties of Arp 220

- Closest Ultra-Luminous Infrared Galaxy (ULIRG)
- Late stage merging galaxy
  - Two nuclei separated by ~ 1” ~ 370 pc.
  - Nuclei are embedded in counter-rotating disk
- ISM properties:
  - $L_{FIR} \sim 10^{11.5-12.5}\ L_\odot \sim 10^{45}$ erg/s
  - $M_{H2} \sim 10^9\ M_\odot$
  - B ~ few mG

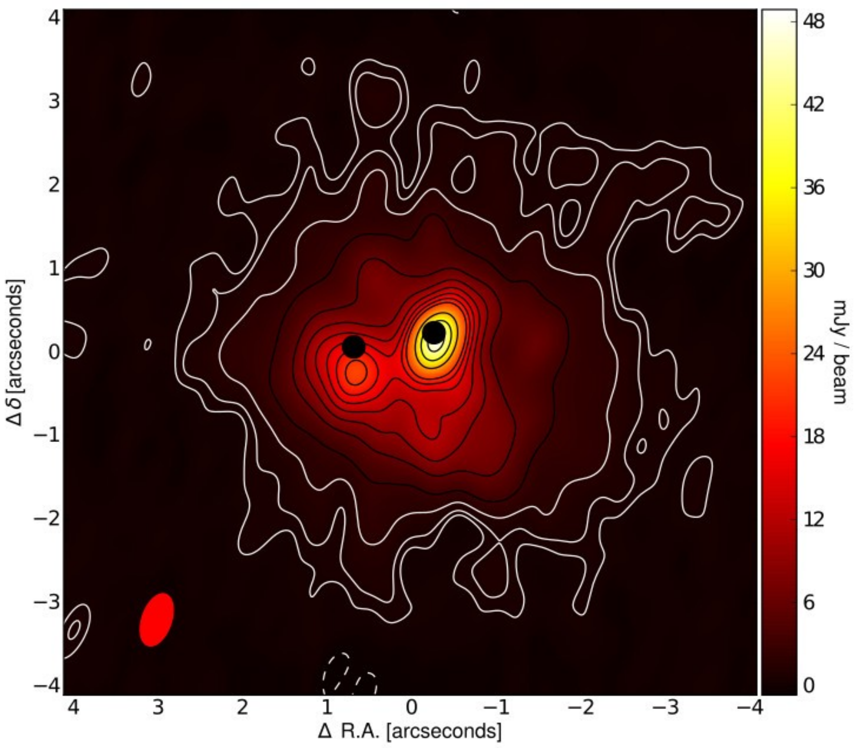


Scoville+ 2017
ApJ, 836, 66
ALMA Band 3



The Central Nuclei of Arp 220

- Power from star formation:
  - SFR ~ 200 $M_\odot$ yr^{-1}
  - SN Rate ~ 2 – 4 yr^{-1}
    - See SNRs with VLBI
- Power from an AGN?
  - Observations of centers hindered by dust obscurration
  - The usual indicators for AGN are not applicable.
    - mm emission lines
    - dust temperature
    - X-rays



Varenius+ 2016,
A&A, 593, 86
LOFAR 150MHz

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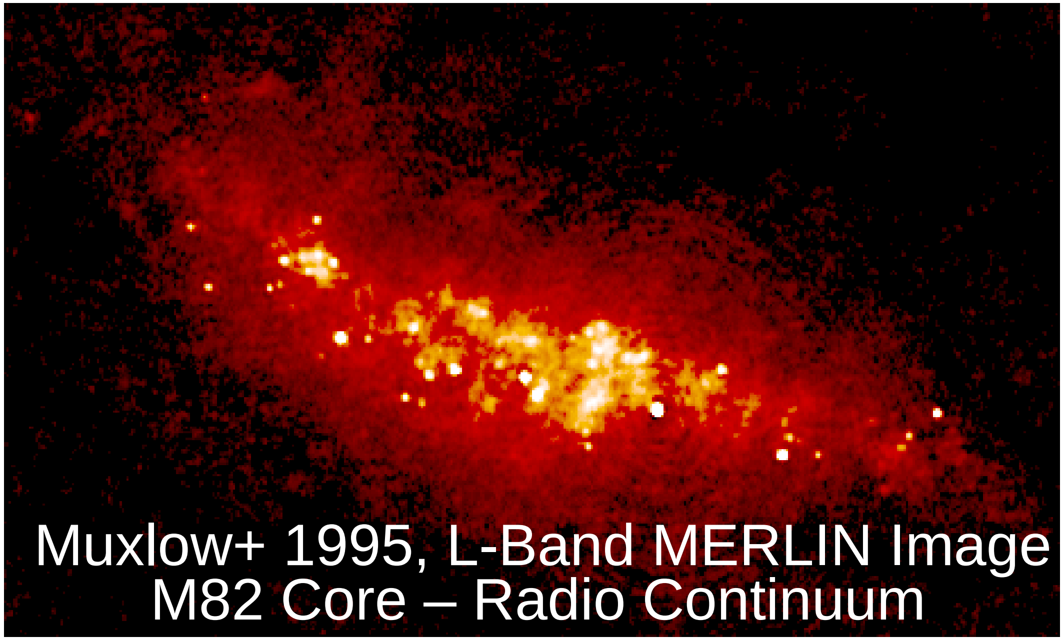
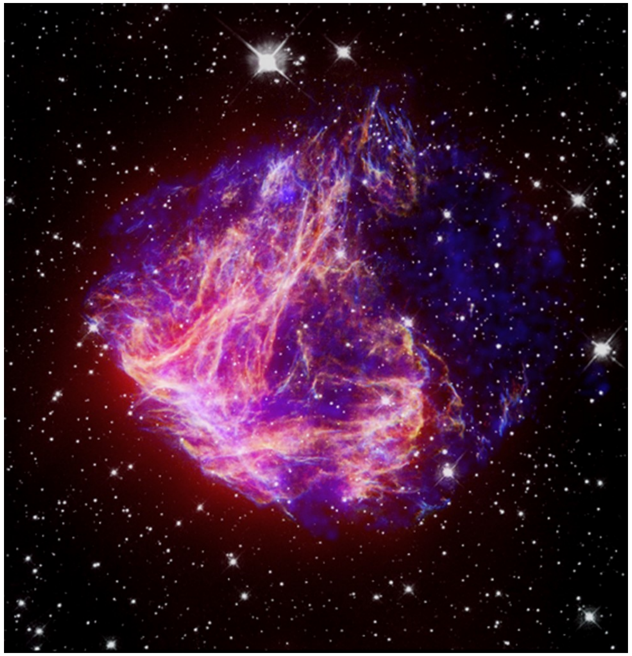


Star Formation Model



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

Fraction of SN Energy into CRs: $\eta \sim 0.05 - 0.2$

Proton to Electron Ratio: $Q_p / Q_e = 50$

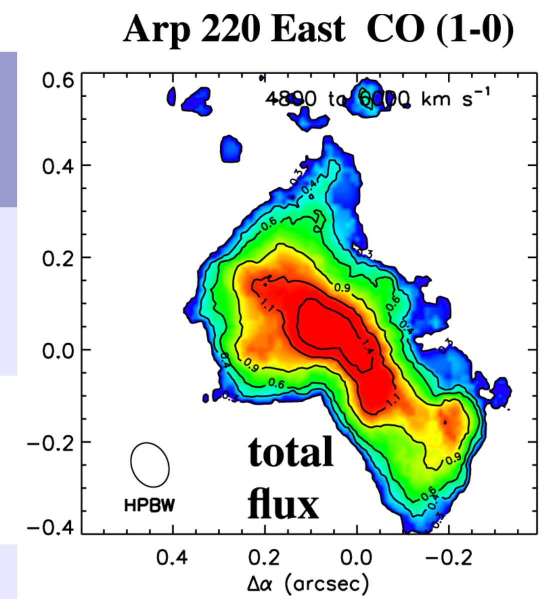
Yoast-Hull+ 2013, ApJ, 768, 53

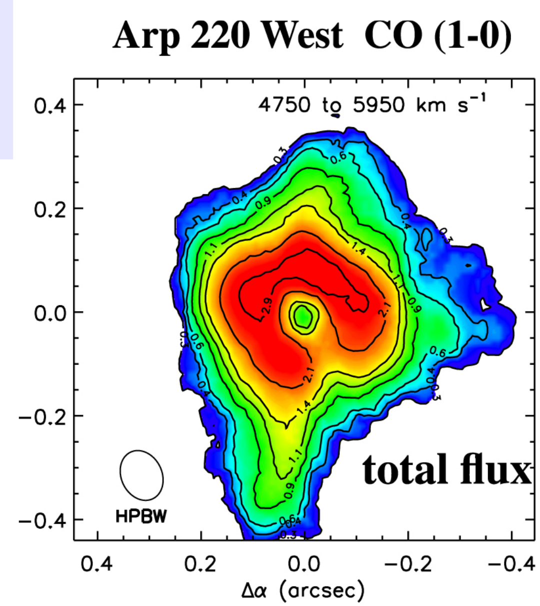
- SNRs are primary CR accelerators.
- Secondary e+/- are included in all leptonic emission calculations.
- U_B and U_{CR} are not assumed to be coupled.

Arp 220 Nuclear Properties

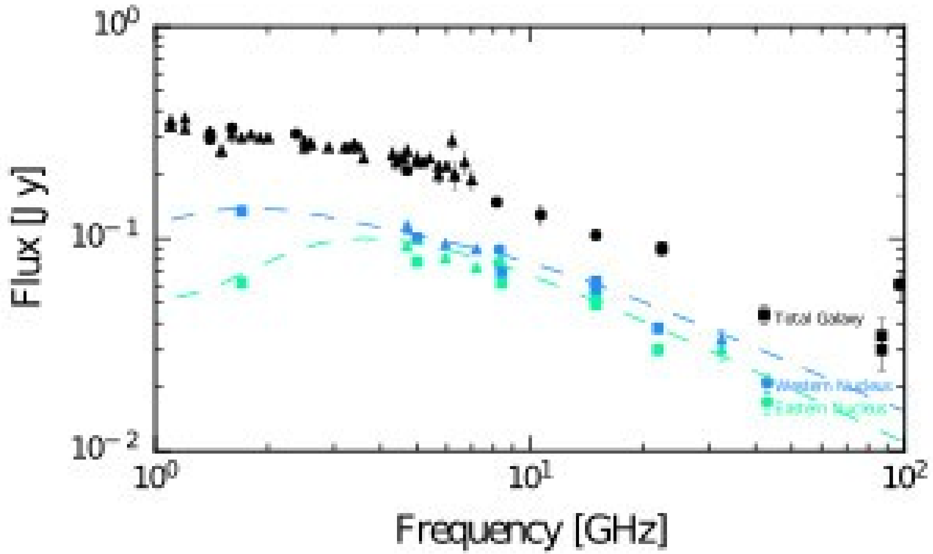
	East	West	CND
Radius (pc)	70	90	30
SN Rate (yr^{-1})	0.7	0.7	1.4
FIR Luminosity ($L_\odot$)	3×10^{11}	3×10^{11}	6×10^{11}
Molecular Mass ($M_\odot$)	6×10^{8}	4×10^{8}	6×10^{8}

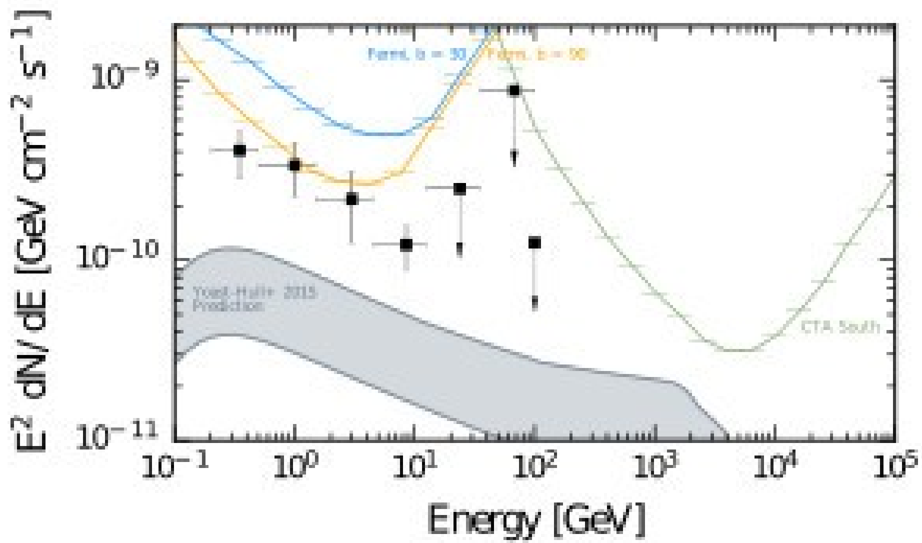
Yoast-Hull+ 2015, MNRAS, 453, 222





Radio Synchrotron Predictions

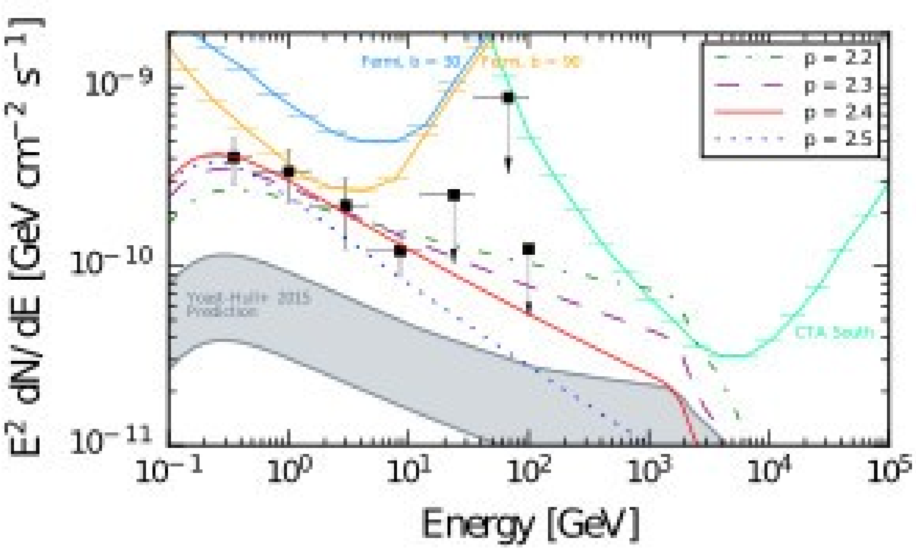




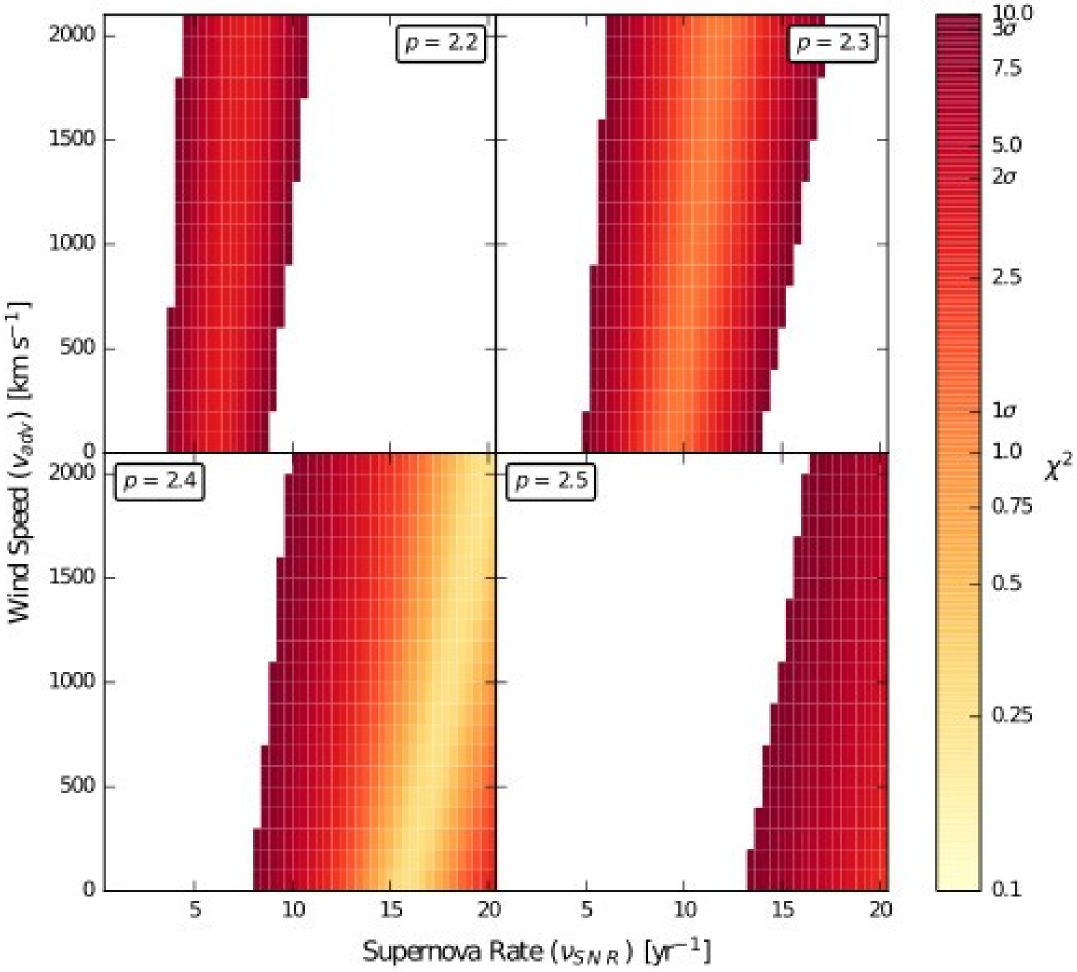
- Achieve good fits to the radio spectra for both nuclei based on observed supernova rate.
- Gamma-ray predictions fall short of the *Fermi* observations.
- How much additional energy into cosmic rays is necessary to match gamma-rays?

Yoast-Hull+ 2015, MNRAS, 453, 222

Gamma-Ray Implications



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



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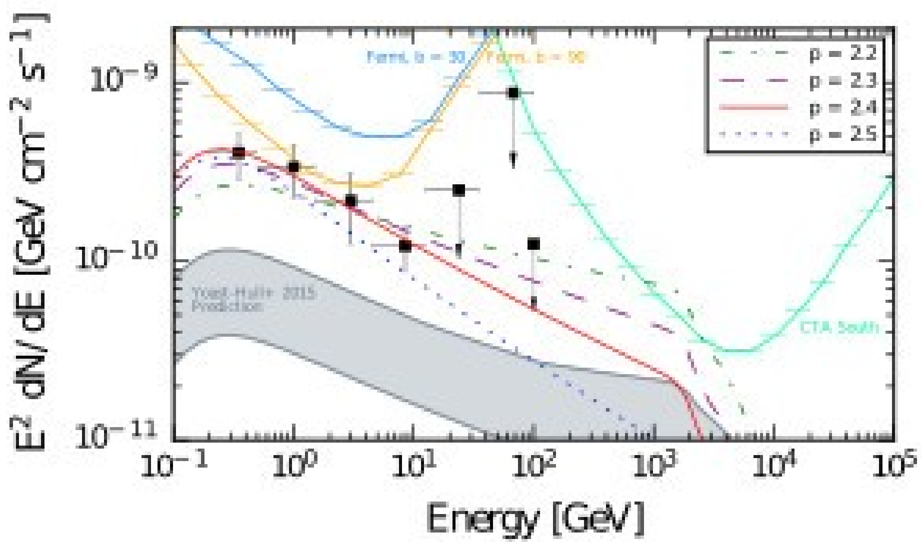
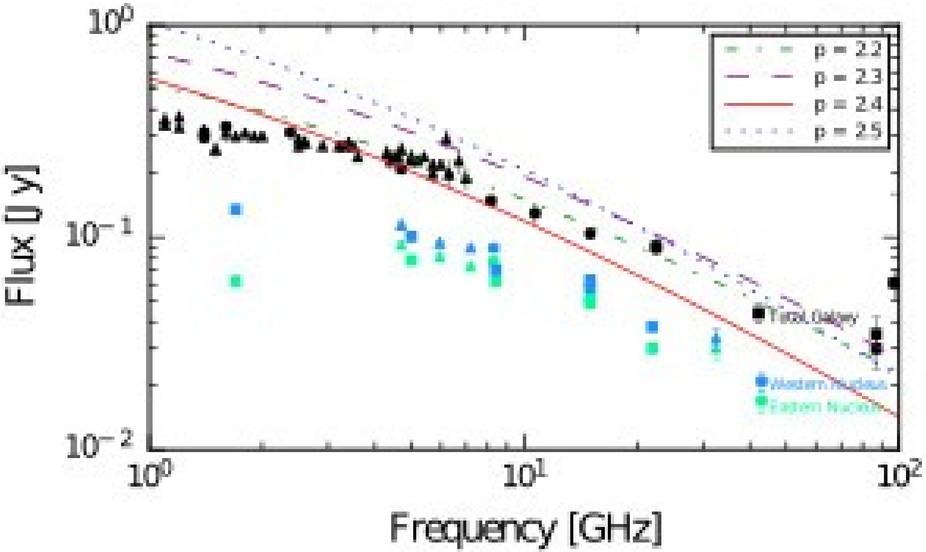
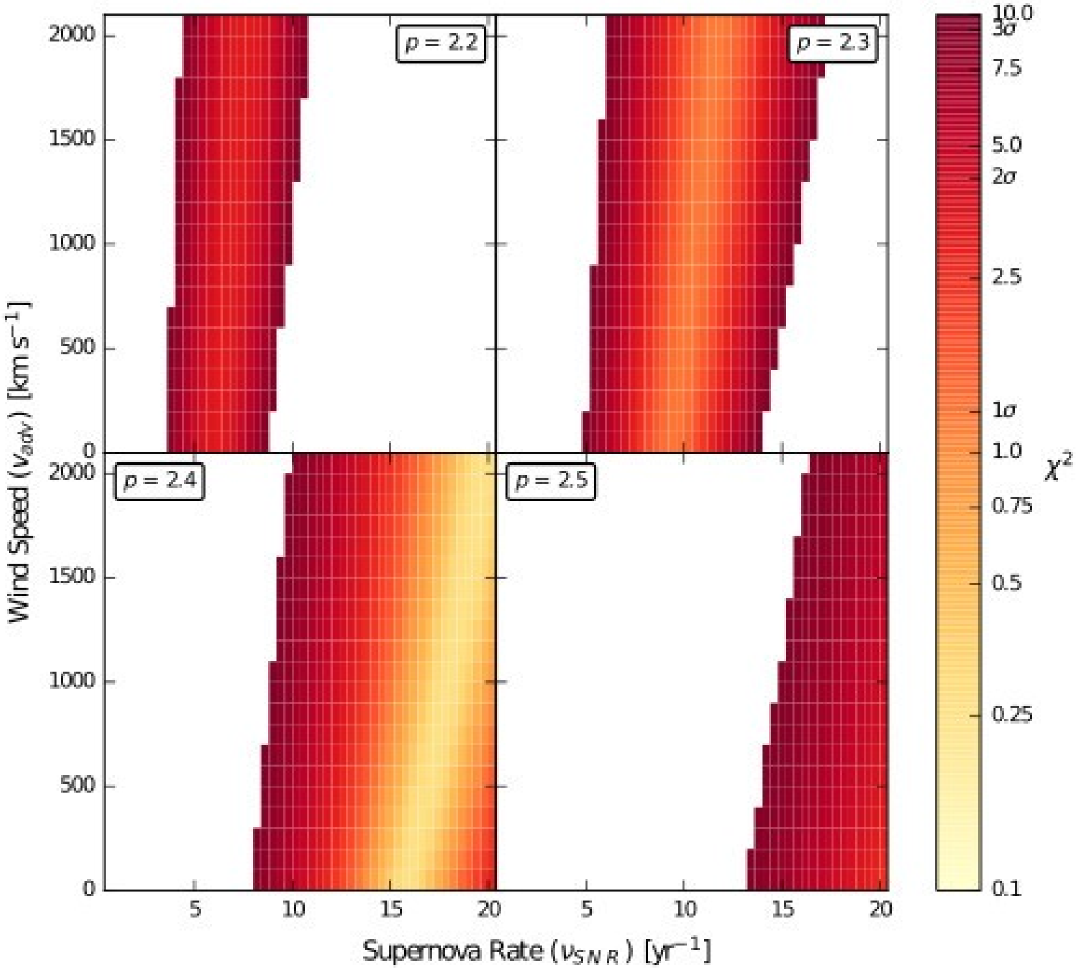


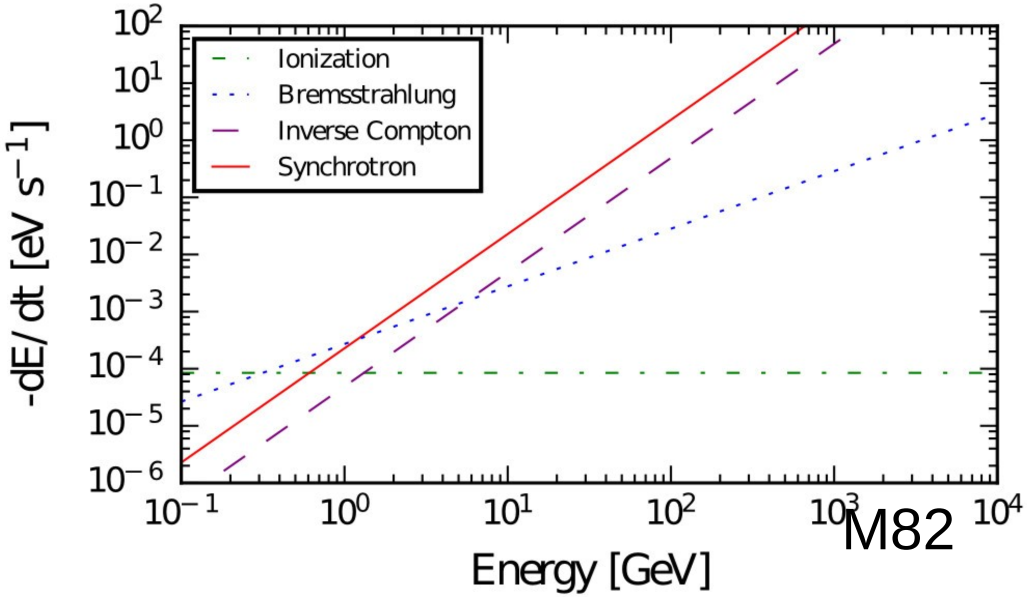


Yoast-Hull+ 2017,
MNRAS, 469L, 89



Cosmic Ray Electrons

- Competitive energy loss processes:
  - Bremsstrahlung
  - Inverse Compton
  - Synchrotron



$$-\left(\frac{dE}{dt}\right)_{e,brem} \propto n_{ISM} E_e$$

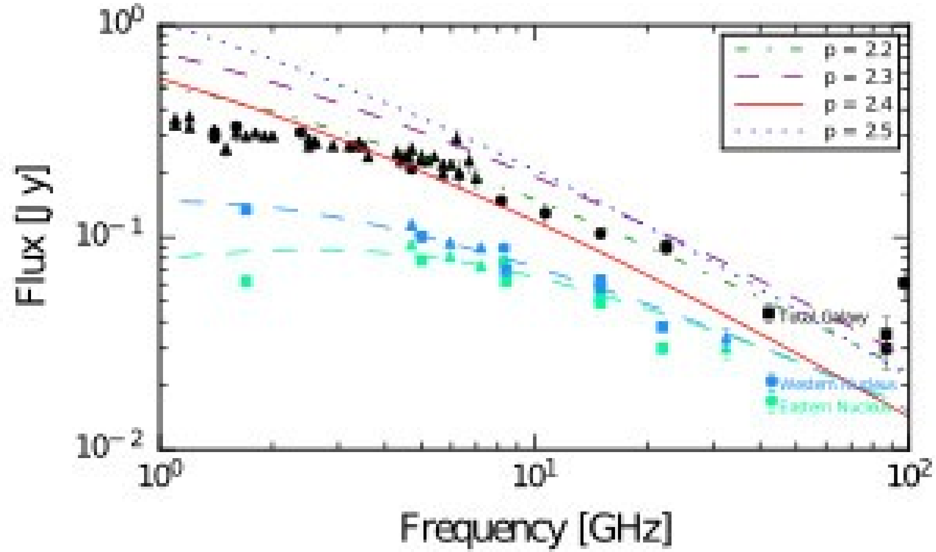
$$-\left(\frac{dE}{dt}\right)_{e,IC} \propto U_{rad} E_e^2$$

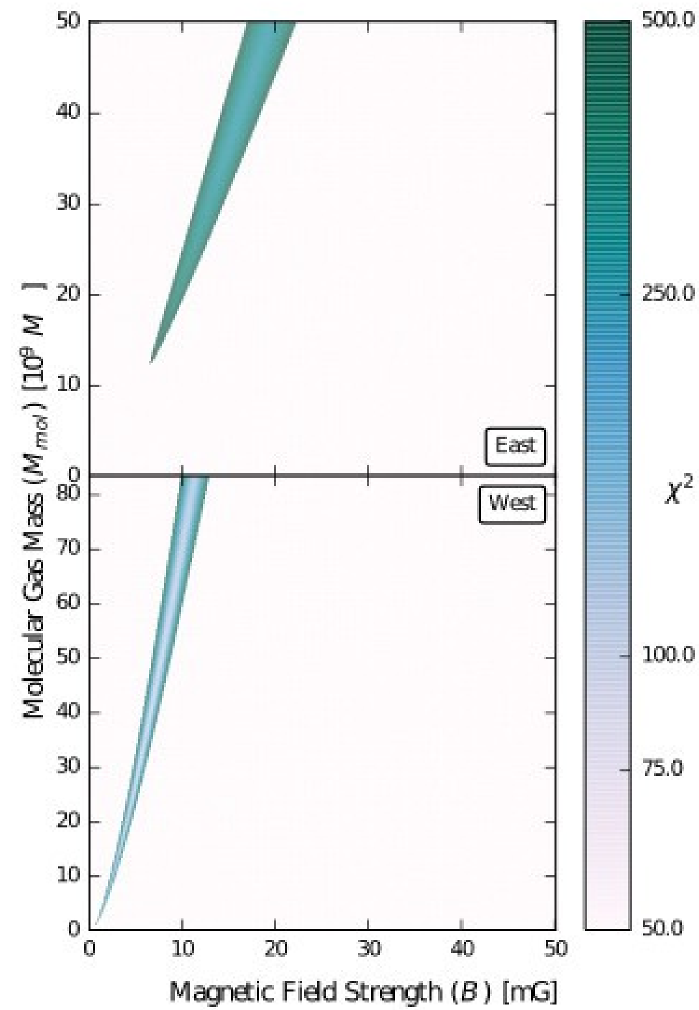
$$-\left(\frac{dE}{dt}\right)_{e,synch} \propto U_B E_e^2$$

Yoast-Hull+ 2013, ApJ, 768, 53

Interstellar Medium Density

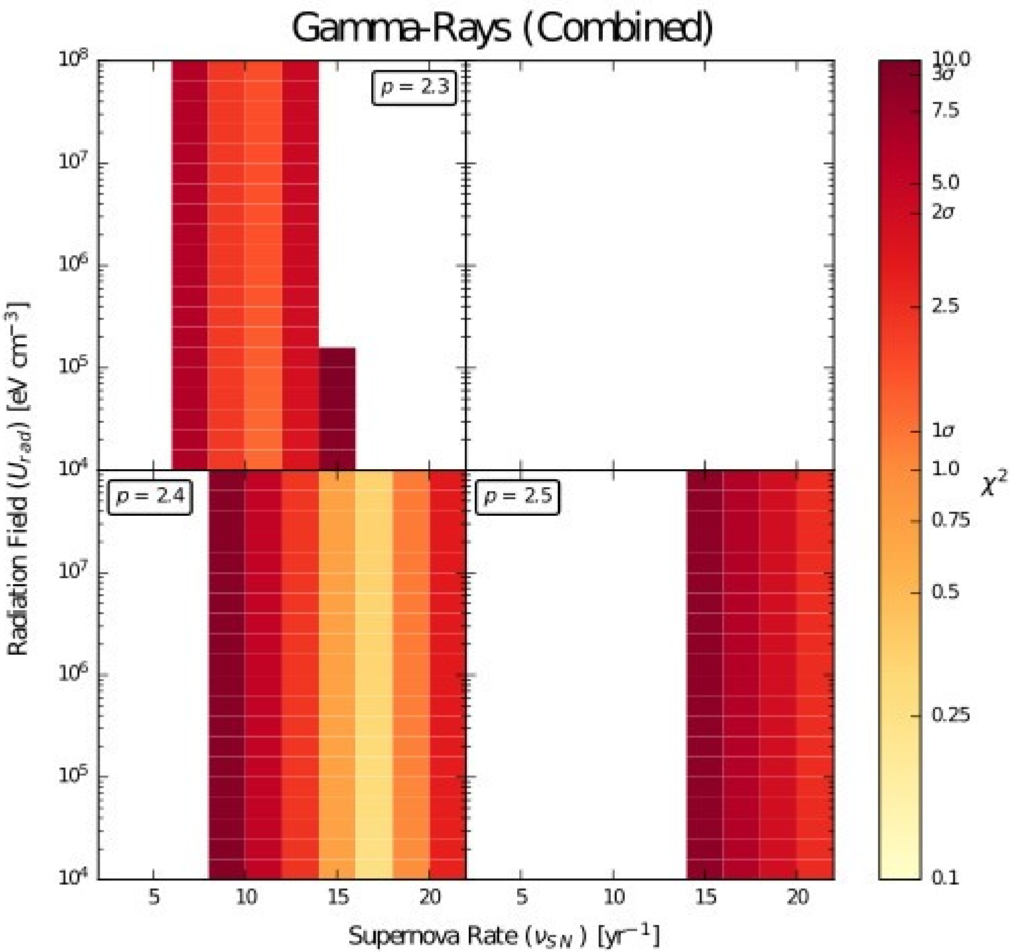
Yoast-Hull+ 2017, MNRAS, 469L, 89





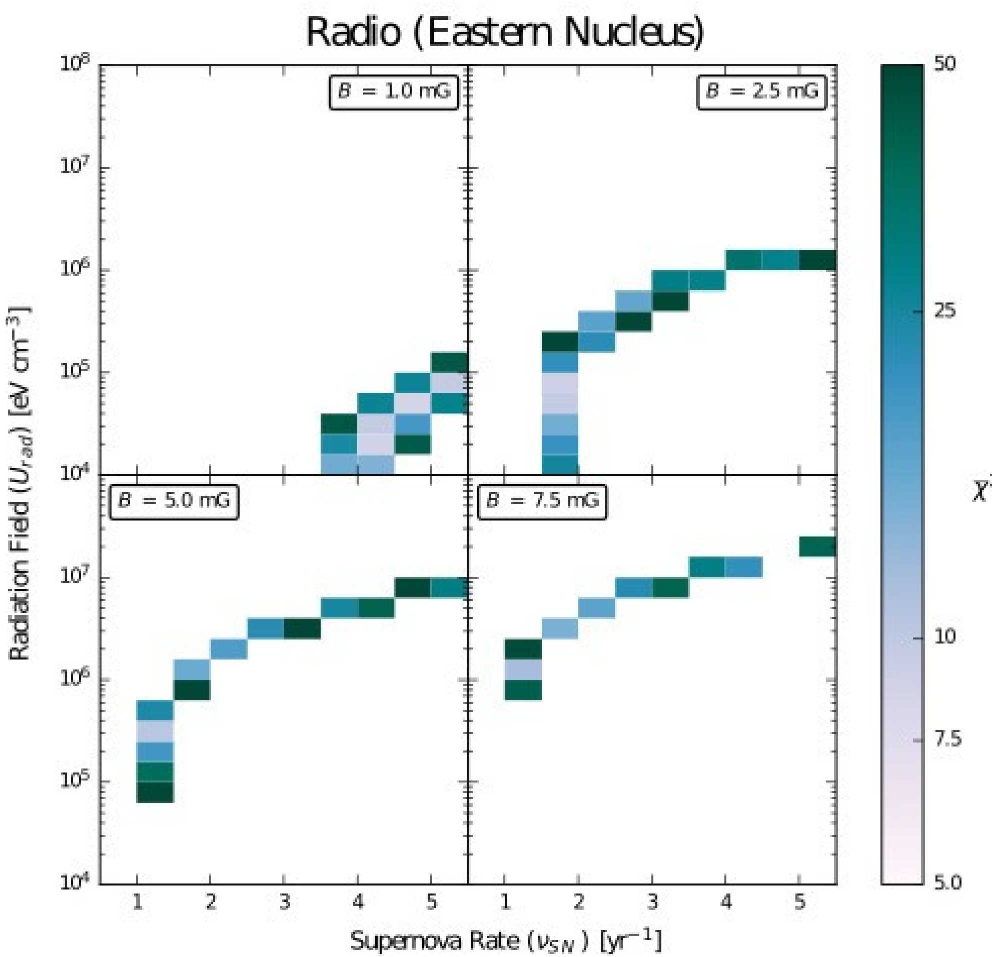
- Increase in molecular gas mass of factor of >10 is necessary to match the observed radio emission.
- Increase this large is unphysical.

Radiation Field Energy Density

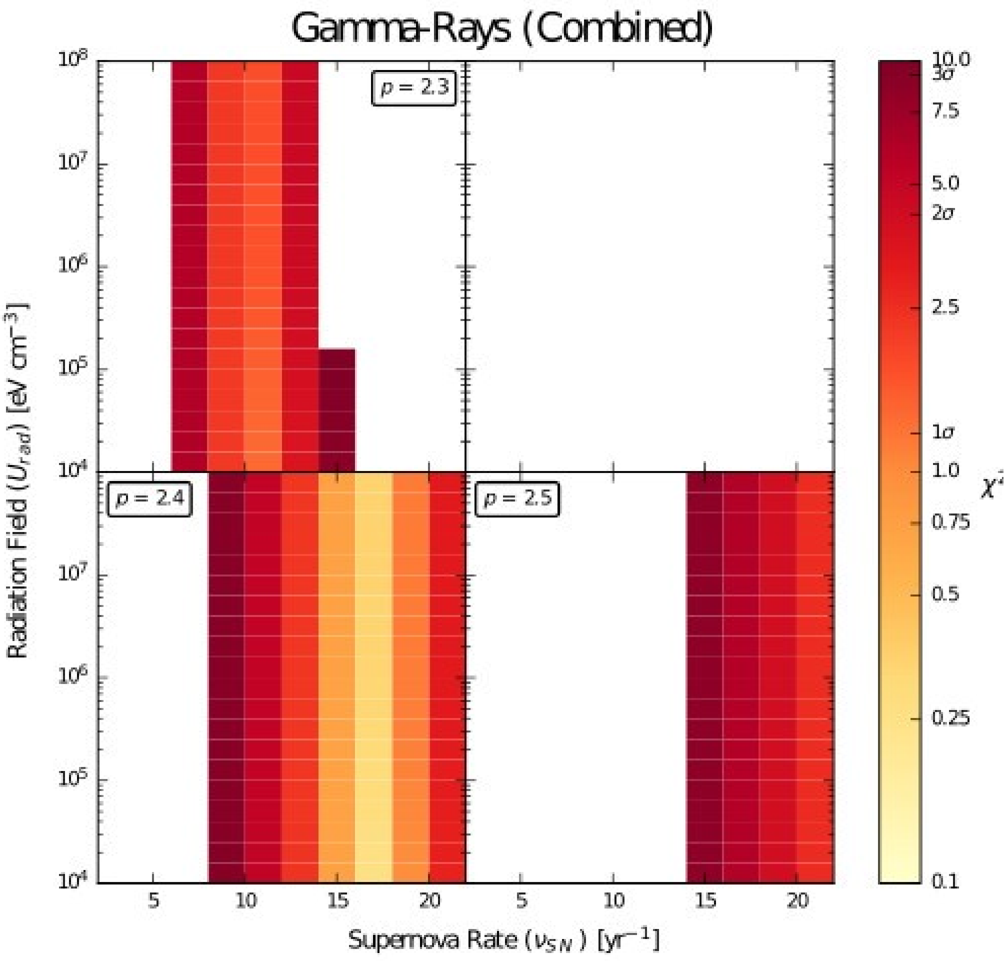


$$U_{IR} = \frac{\tau L_{IR}}{4 \pi R^2 c}$$

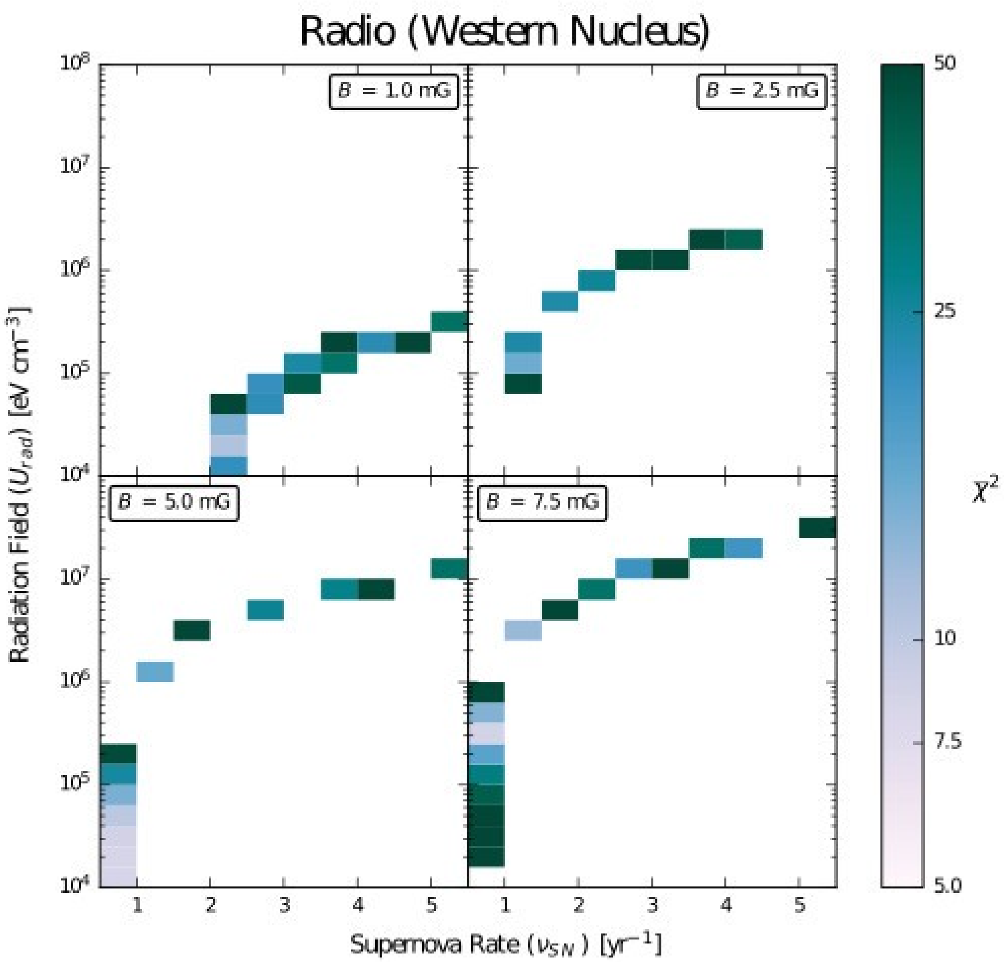
Yoast-Hull+ 2017,
In prep



Radiation Field Energy Density



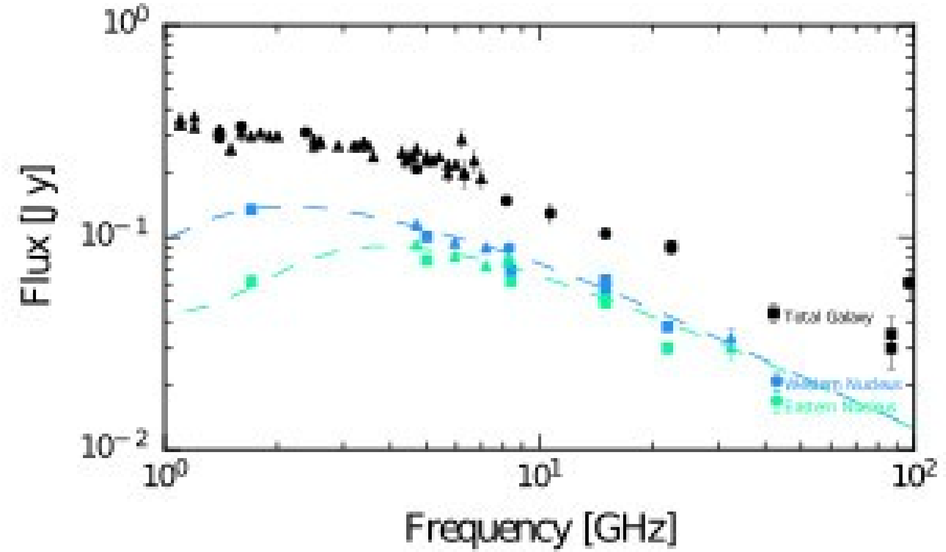
Yoast-Hull+ 2017,
In prep



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

Conclusions

- There is an overabundance of gamma-rays compared to the radio (and the SFR).
- CR energy requirements for the gamma-rays are factors of 4 – 8 larger than suggested by observations.
- To lower the radio emission, IR opacities of 5 – 1000 are necessary.
- Further testing of the radio models (particularly the thermal component) is required.



Yoast-Hull+ 2017,
In prep