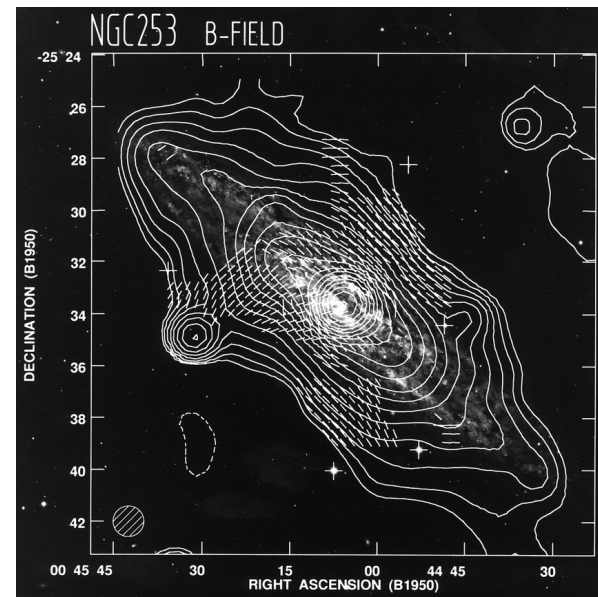
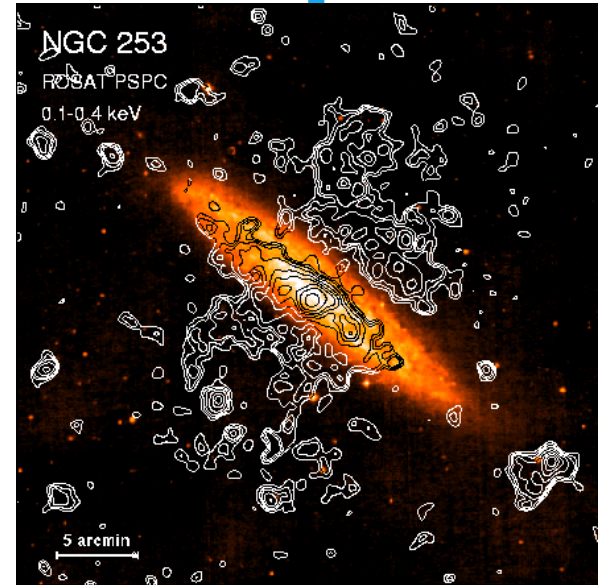


Starburst Galaxies: A Multi-Messenger Perspective

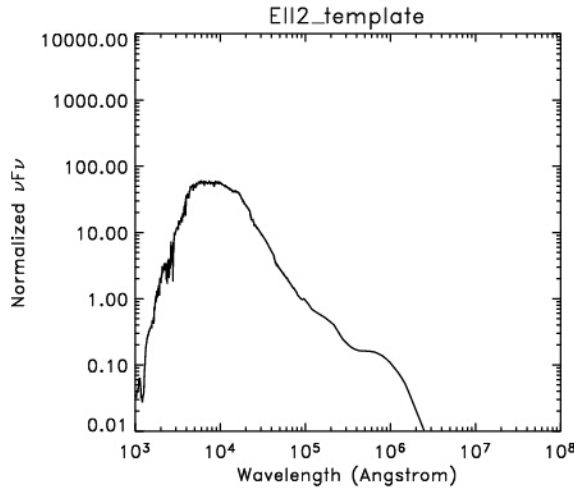


Starburst Galaxy: NGC 253

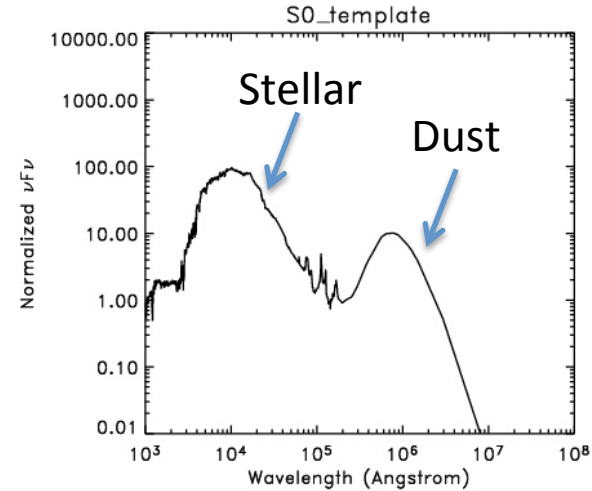


Galaxy Spectral Templates

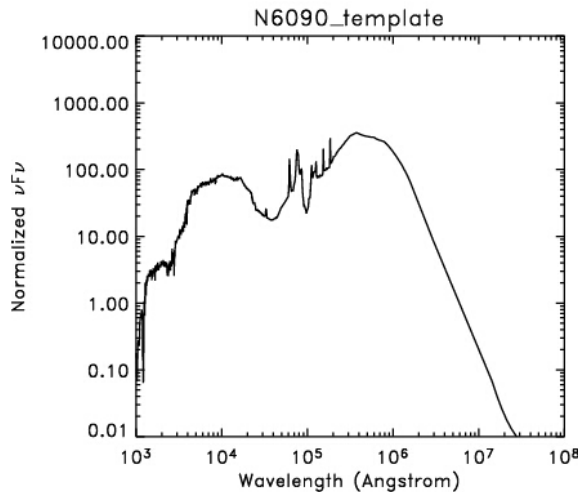
Elliptical Galaxies



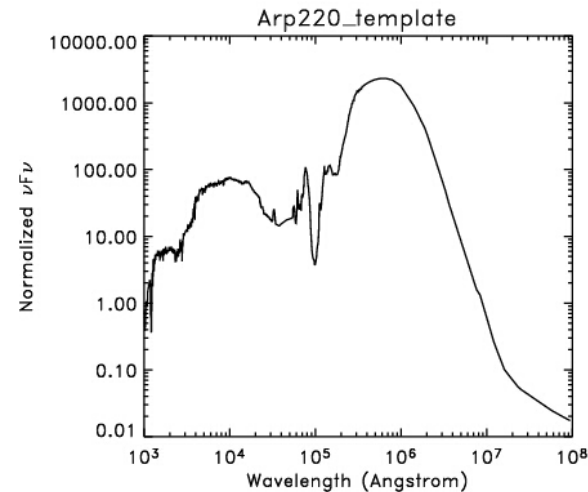
Spiral Galaxies



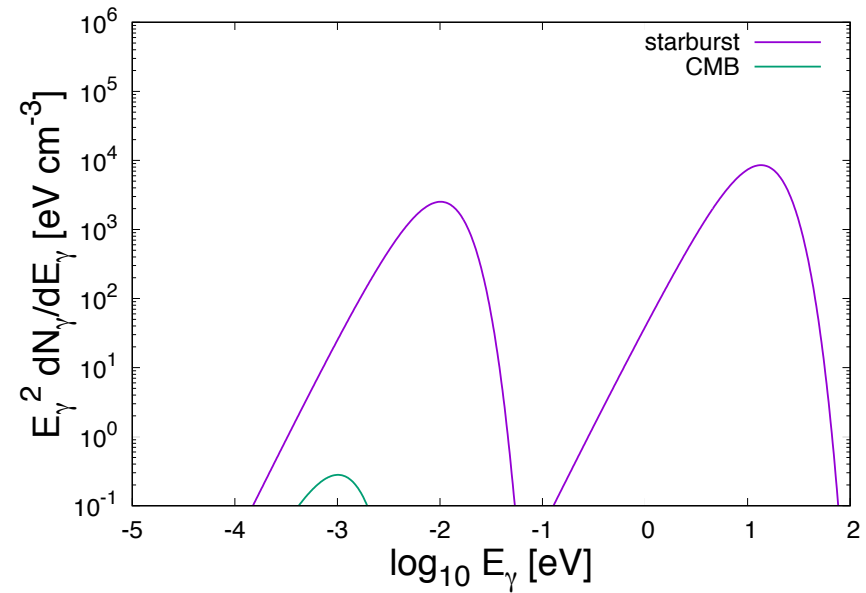
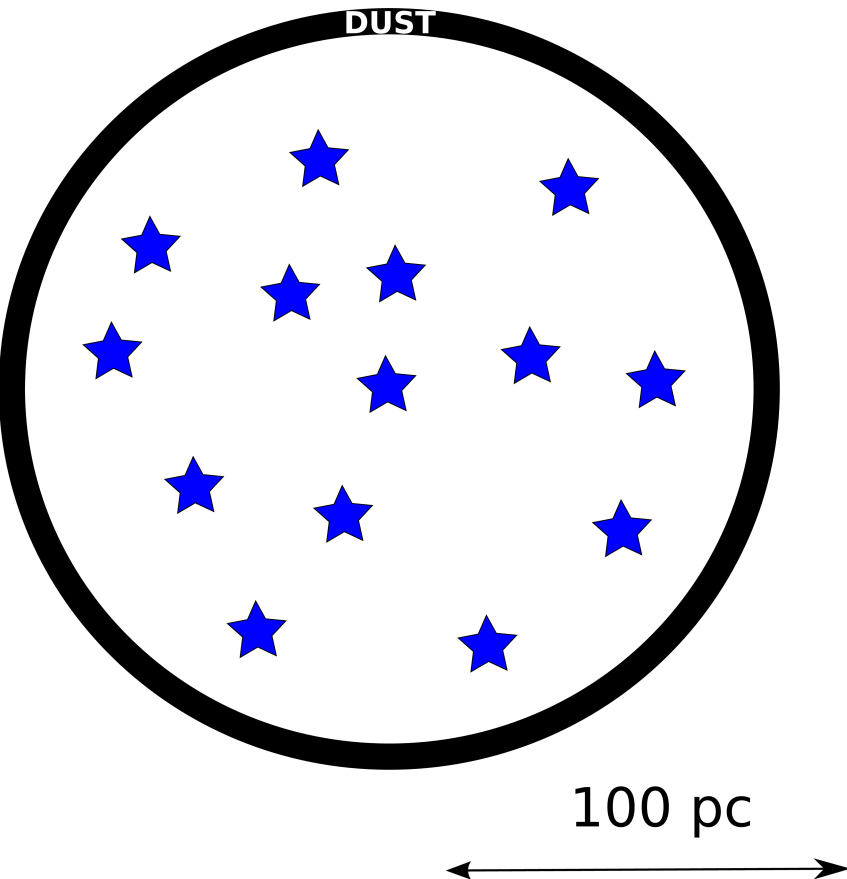
Starburst Galaxies



Ultra Luminous Infrared Galaxies



Stars and Dust



As nuclear star formation increases, both stellar radiation and dust increase, resulting in a larger growth of IR light than stellar light

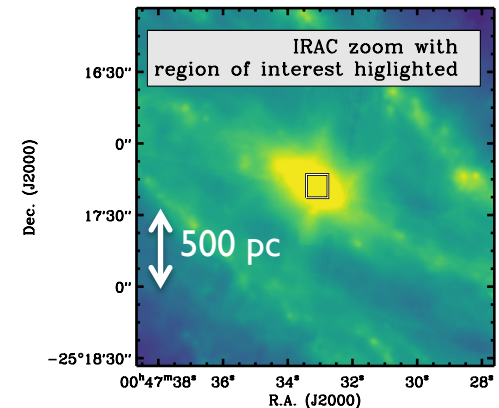
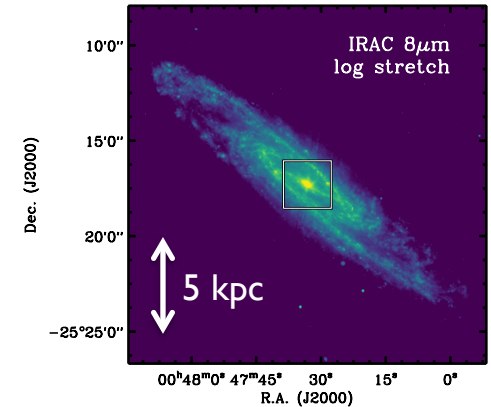
Thermal Emission Zones

50% of the star formation
occurs in the Galactic
nucleus of NGC 253

Nuclear star-formation rate:
 $\sim 2 \text{ M}_{\odot} \text{ yr}^{-1}$

Estimations suggest that
~50% of mass in starburst
region is now in stars

$$L_{\gamma}^{\text{IR}} \approx 3 \times 10^{43} \text{ erg s}^{-1}$$

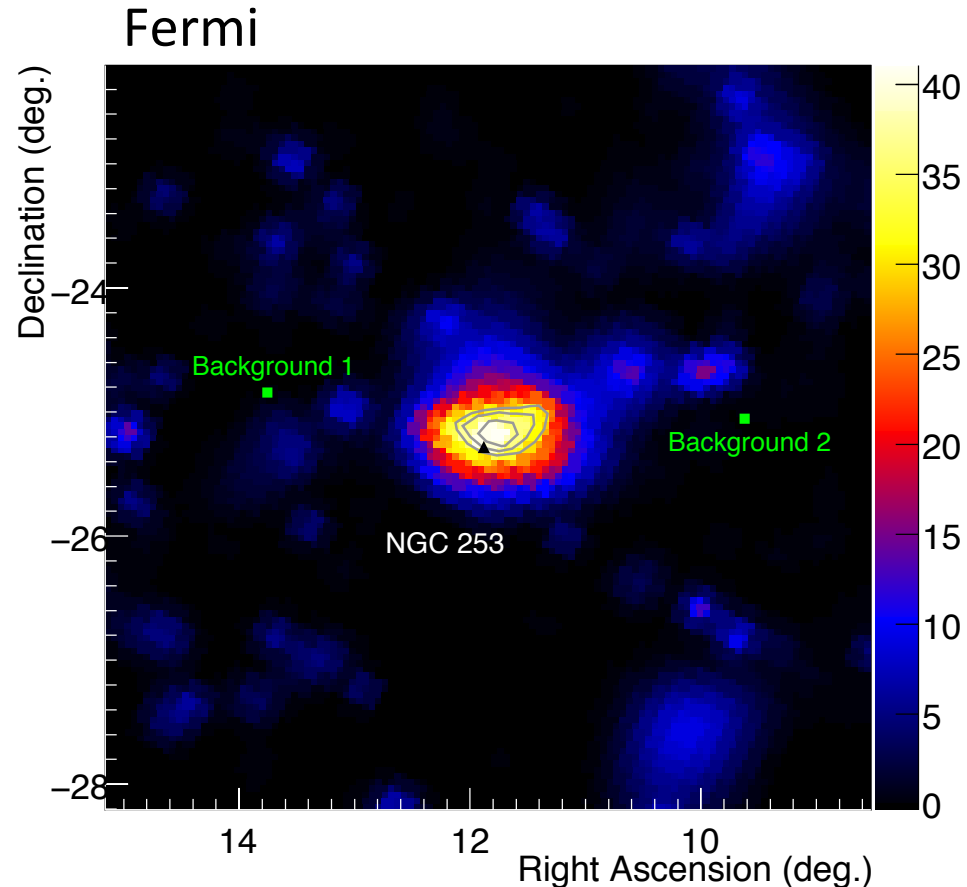


A. Leroy+ 2018

NGC 253: Gamma-Ray Emission Perspective

Gamma-Ray Contour Map-
rather poor spatial information

- No evidence for extension found at either GeV (Fermi) or TeV (HESS) energies.
- GeV observations place constraint of emission sight be < 19 kpc from Galactic nucleus
- TeV observations constrain the emission region to be < 1.5 kpc from Galactic nucleus



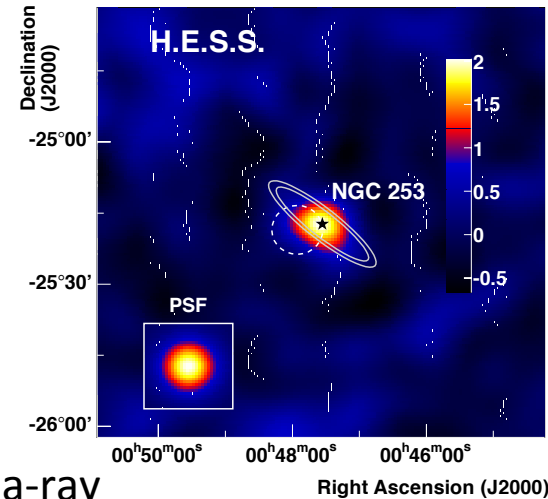
Abdo +, Ap.J. 709 (2010)

NGC 253: On Small and Big Scales

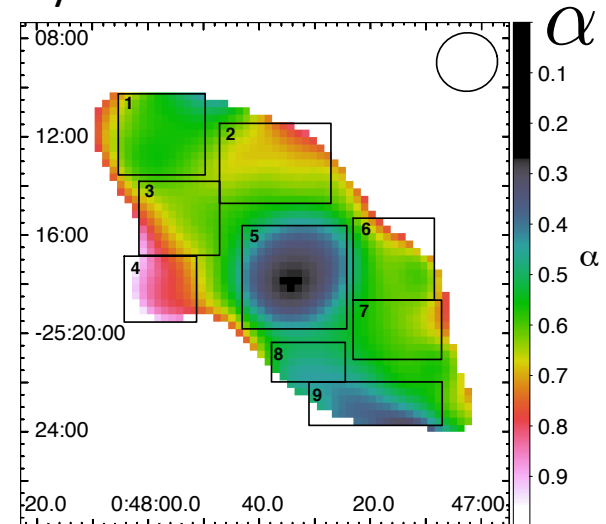
Abramowski+, ApJ 757 (2012)



(Just one example of a hadronically powered gamma-ray emitting galaxy- HAG)



Small Scale



Big Scale

How kind nature is to us!

DESIGN.

Sep, 2019

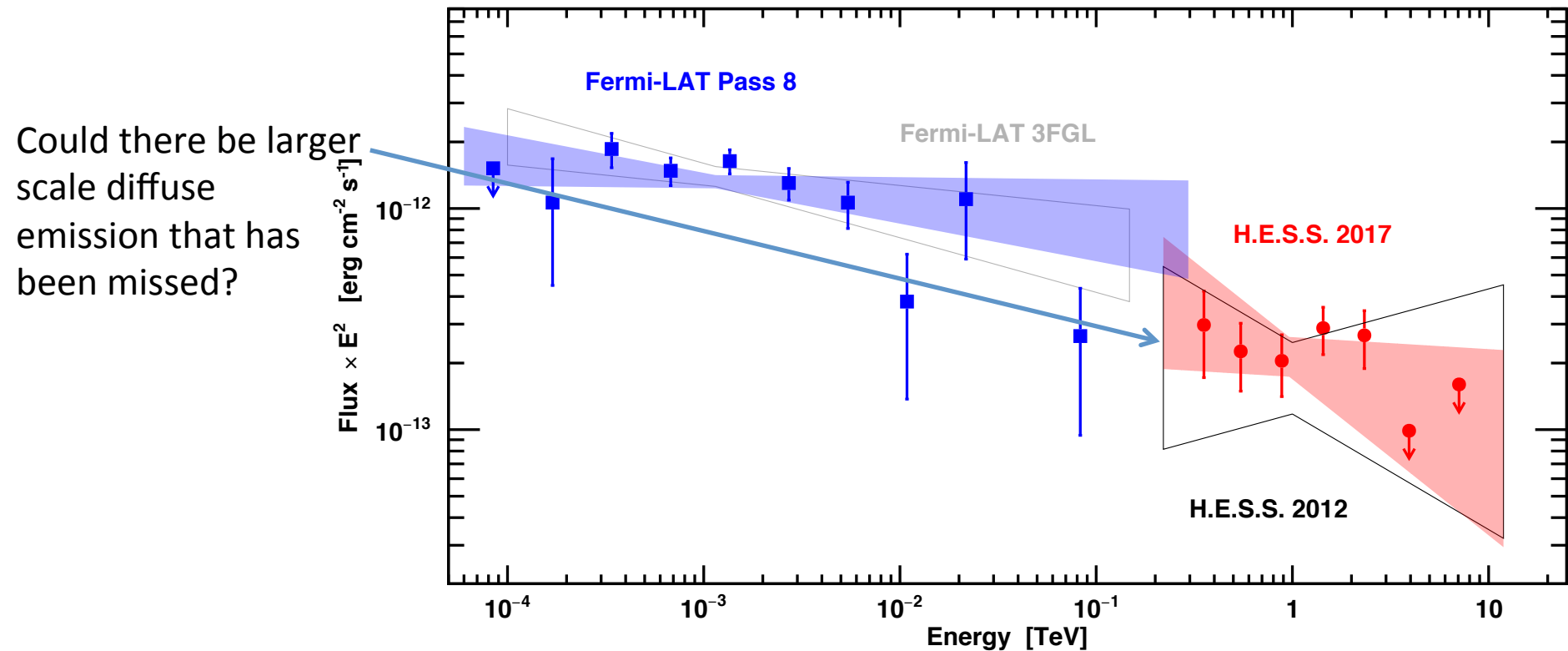
Kapinska+, ApJ 838 (2017)



NGC 253: Gamma-Ray Spectrum

Gamma-Ray Spectral Coverage-
very good energy information

$$L_{\gamma}(\text{GeV}) \approx 10^{40} \text{ erg s}^{-1}$$



Do cosmic ray protons dump all their energy within the source, or are some fraction of them able to escape?

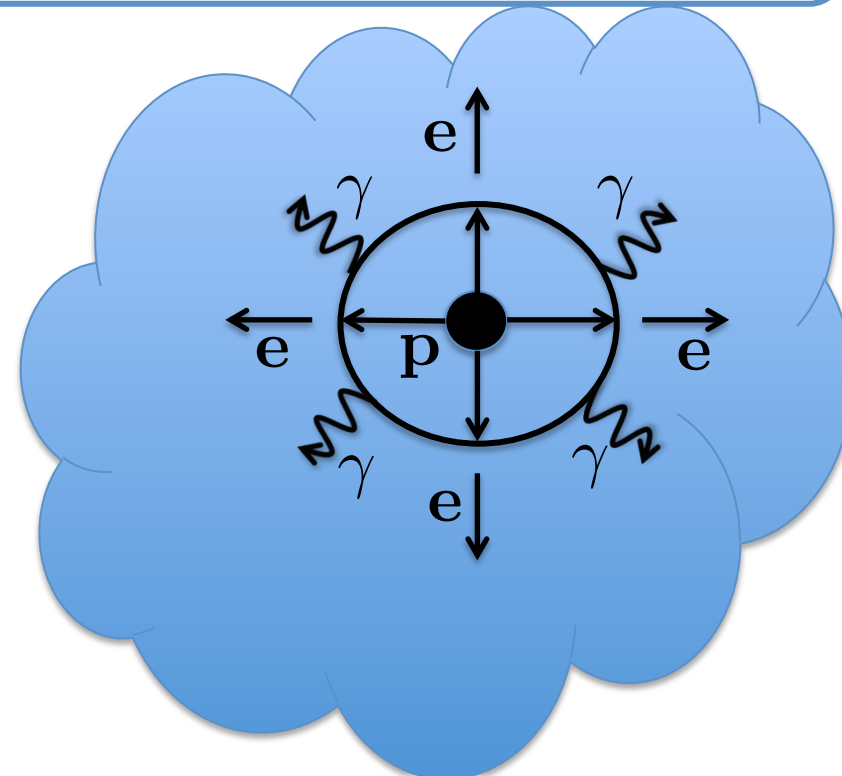
Cosmic Ray Calorimetry

$$X_{\min} = \rho R_{\text{cloud}} \approx 0.015 \left(\frac{n}{500 \text{ cm}^{-3}} \right) \left(\frac{R}{10 \text{ pc}} \right) \text{ g cm}^{-2}$$

$$X \approx \rho R_{\text{cloud}} \left(\frac{R_{\text{cloud}}}{D/c} \right) \approx 1.5 \left(\frac{n}{500 \text{ cm}^{-3}} \right) \left(\frac{R_{\text{cloud}}}{10 \text{ pc}} \right)^2 \left(\frac{0.1 \text{ pc}}{D/c} \right) \text{ g cm}^{-2}$$

$$L_{\gamma} = \left(1 - e^{-t_{\text{esc}}/t_{\text{pp}}} \right) L_{\text{p}} \approx \left(\frac{t_{\text{esc}}}{t_{\text{pp}}} \right) L_{\text{p}}$$

Calorimetric sources have gamma-ray spectrum which mimics that of parent protons.



NGC 253: Hadronic Colorimetric Fraction Estimation

- Calorimetric fraction estimate
→ How much of the available CR power goes into pion production?
- Fraction of particles able to do pion production:

$$f_{\text{cal}} = \frac{L_{\pi}}{L_{\text{CR}}(> E_{\pi}^{\text{th.}})} \approx 0.3 \left(\frac{0.7}{f_{\pi}} \right) \left(\frac{L_{\gamma}}{10^{40} \text{ergs}^{-1}} \right) \left(\frac{2 \times 10^{41} \text{ergs}^{-1}}{L_{\text{CR}}} \right)$$

NGC 253: Gamma-Ray Perspective

- CR Luminosity from astrophysical parameters

Thin + Thick Target Spectra:

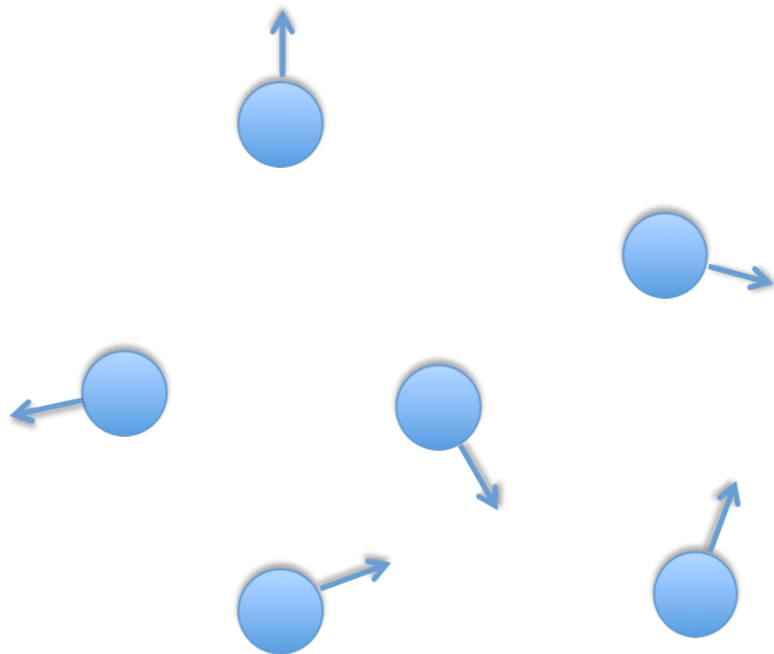
$$\frac{\partial}{\partial t} n(\mathbf{p}, t) = Q(\mathbf{p}, t) - \frac{n(\mathbf{p}, t)}{\tau_{\text{loss}}(\mathbf{p})} - \frac{n(\mathbf{p}, t)}{\tau_{\text{esc}}}$$

- Only two ways for particles to leave the box- die in it or escape from it.
- The gas in the starburst as “Thin” or “Thick” target for the CRs, depending on which of the ways the CRs preferentially leave the system.

How Do Non-Thermal Particles Get Transported Out of the Central Region?

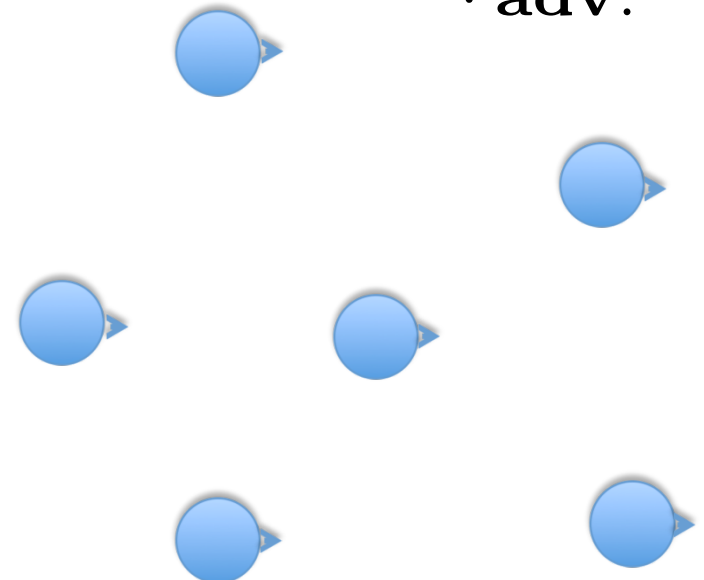
Diffusive Escape

$$t_{\text{diff.}} \approx \frac{R^2}{D}$$



Advective Escape

$$t_{\text{adv.}} = \frac{R}{v_{\text{adv.}}}$$



NGC 253: Transport Timescale

- Escape- Competing Transport Timescales

$$t_{\text{diff.}} \approx \frac{R^2}{D}$$

$$t_{\text{adv.}} = \frac{R}{v_{\text{adv.}}}$$

$$R \approx 100 \text{ pc}$$

$$D/c = 0.1 \text{ pc}$$

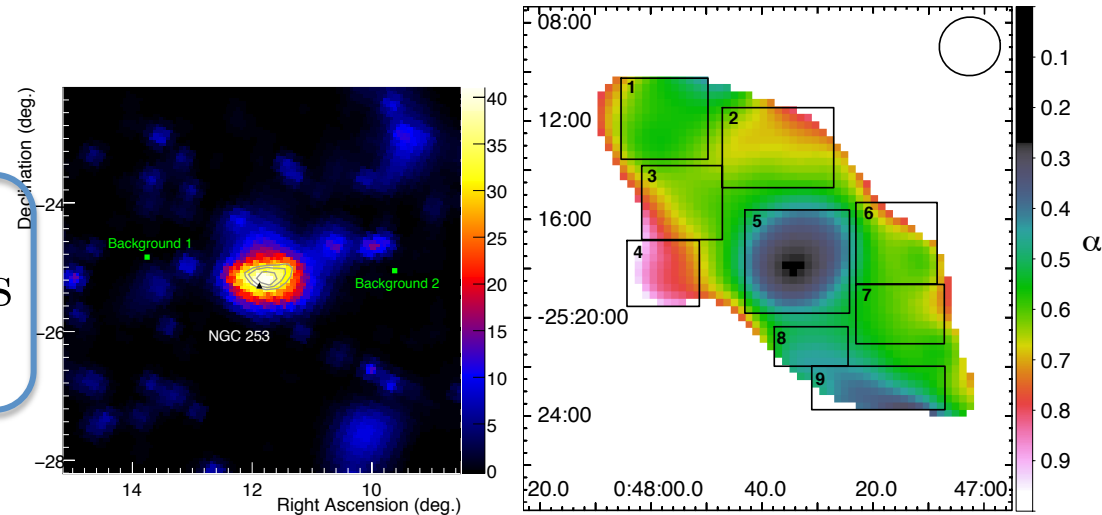
$$v_{\text{adv.}} \approx 300 \text{ km s}^{-1}$$

$$t_{\text{diff.}} = 3 \times 10^5 \text{ yrs}$$

$$t_{\text{adv.}} \approx 3 \times 10^5 \text{ yrs}$$

NGC 253: Energy Loss Emission

$$t_{pp} \approx 10^5 \left(\frac{500 \text{ cm}^{-3}}{n_p} \right) \text{ yrs}$$



$$t_e = 10^5 \left(\frac{5 \text{ GeV}}{E_e} \right) \left(\frac{500 \text{ eV cm}^{-3}}{U_{\gamma/B}} \right) \text{ yrs}$$

$E_\gamma = 5 \times 10^8 \text{ eV}$
Gamma-Rays

DESY.

Radio/Microwave

$$E_\gamma = 10^{-4} (B/150 \mu\text{G}) \text{ eV}$$

Sep, 2019

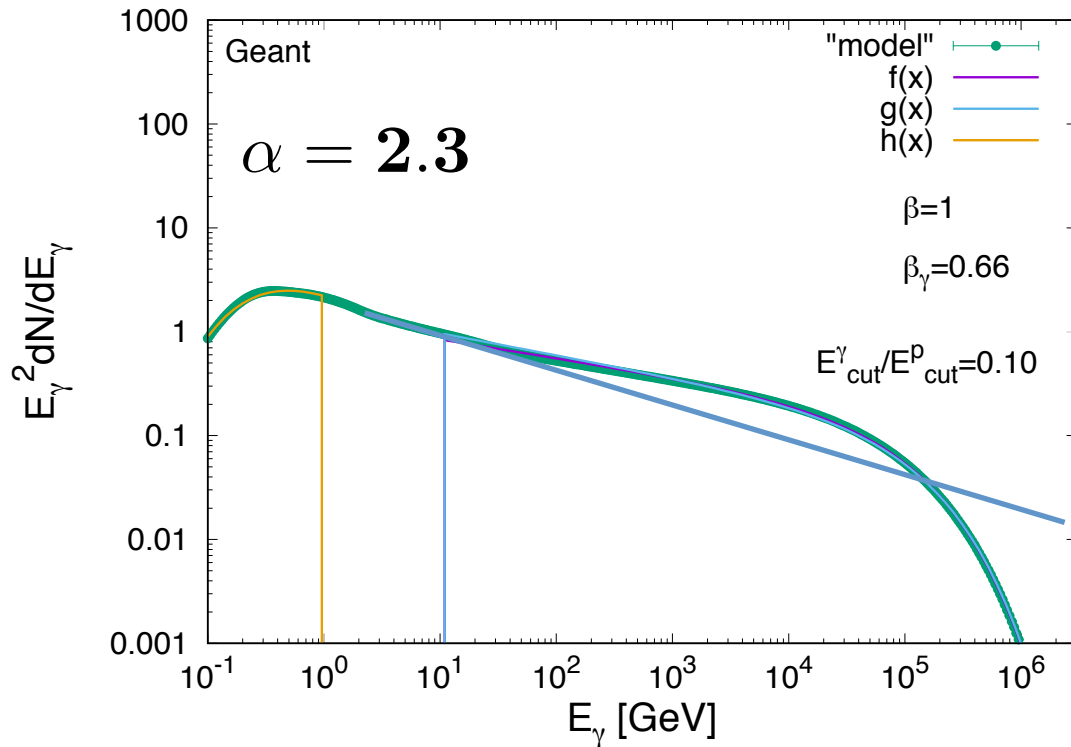


NGC 253: Gamma-Ray Perspective

- The gas in the starburst as “Thin” or “Thick” target for the CRs
- Thick ($\tau_{\text{esc}} \gg \tau_{\text{loss}}$):
 - All particles lose all their energy before they can leave
 - Gamma spectral index = CR spectral index
- Thin ($\tau_{\text{esc}} \ll \tau_{\text{loss}}$):
 - Fraction of the particles escapes the starburst via advection
 - Higher energy CRs lose energy more efficiently
 - Gamma spectral index $\neq$ CR spectral index

NGC 253: Hadronic Gamma-Ray Emission

$$\Phi_{\gamma}(E_{\gamma}) = 4\pi n_{\text{H}} \int \frac{d\sigma}{dE_{\gamma}}(p_p, E_{\gamma}) J(p_p) dp_p$$



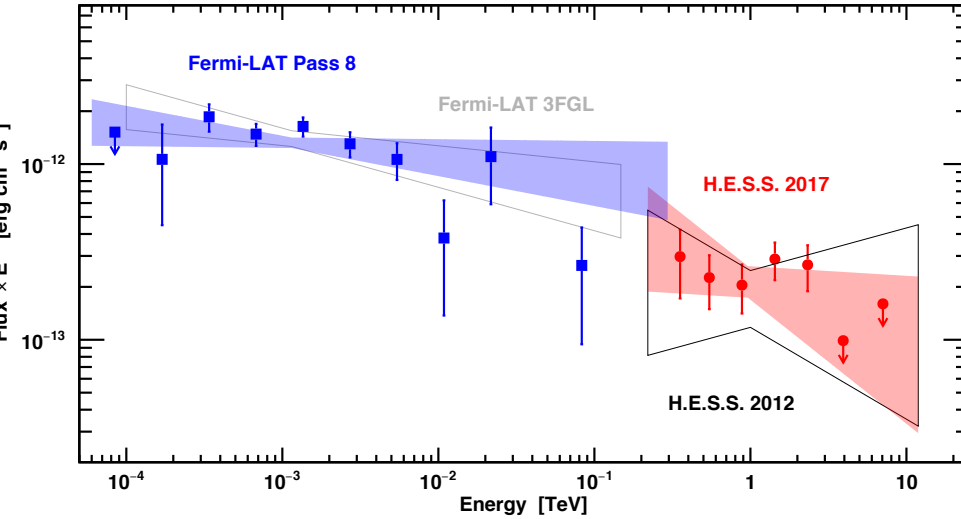
$$J_p(p_p) = \frac{A}{p_p^\alpha} \exp \left[- \left(\frac{p_p}{p_p^{\text{max}}} \right)^\beta \right]$$

Kafexhiu+ Phys.Rev. D90 (2014)

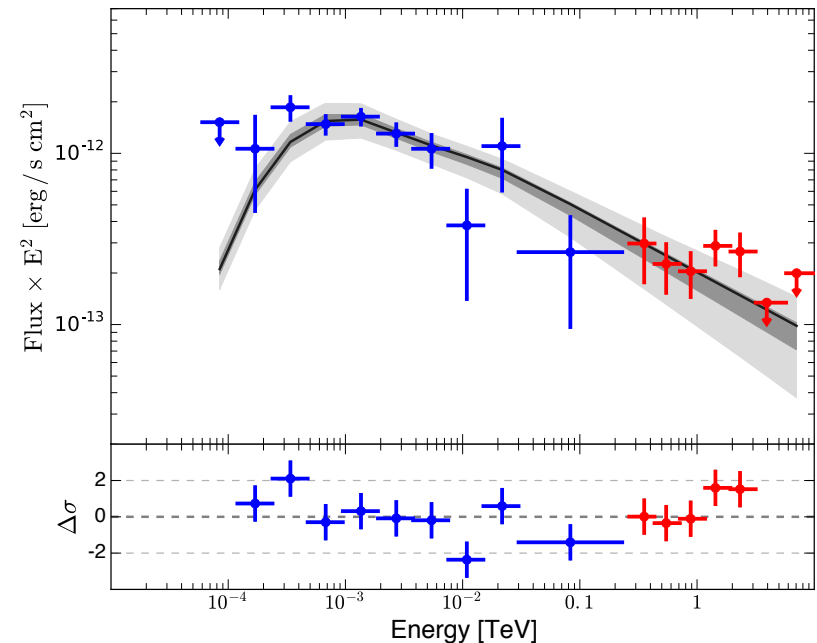
Above threshold, a hardening of the photon spectrum occurs, with the index decreasing by ~ 0.04 each decade.

NGC 253: Gamma-Ray Perspective

- Index = 2.22 ± 0.06 **Thick Target**



- Index = 2.46 ± 0.03 **Thin Target**



NGC 253: Hadronic Colorimetric Fraction Estimation

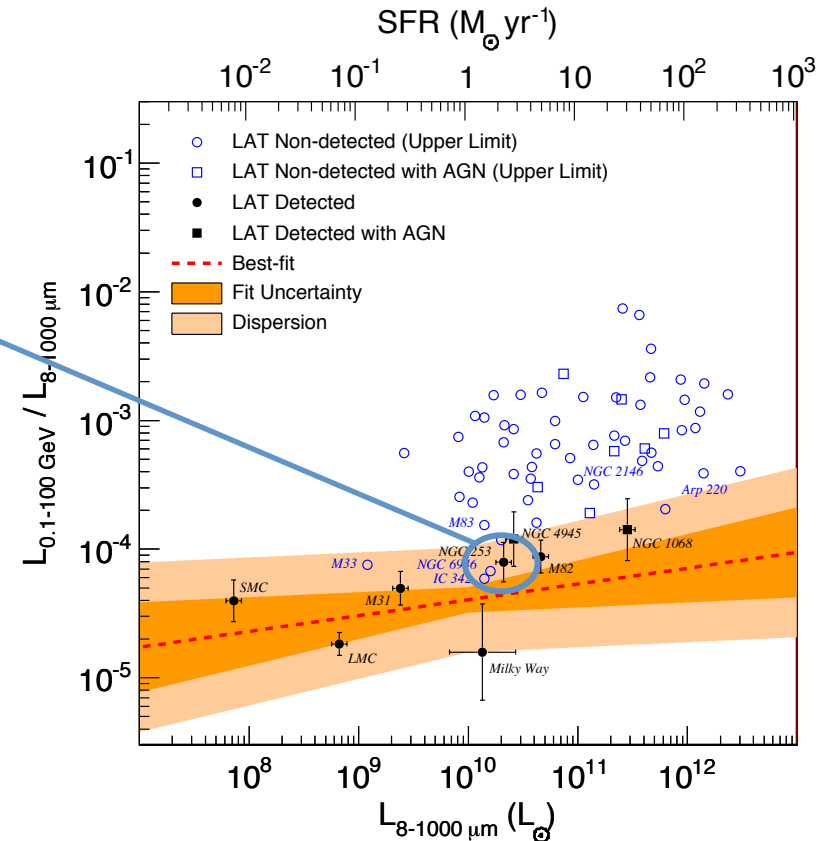
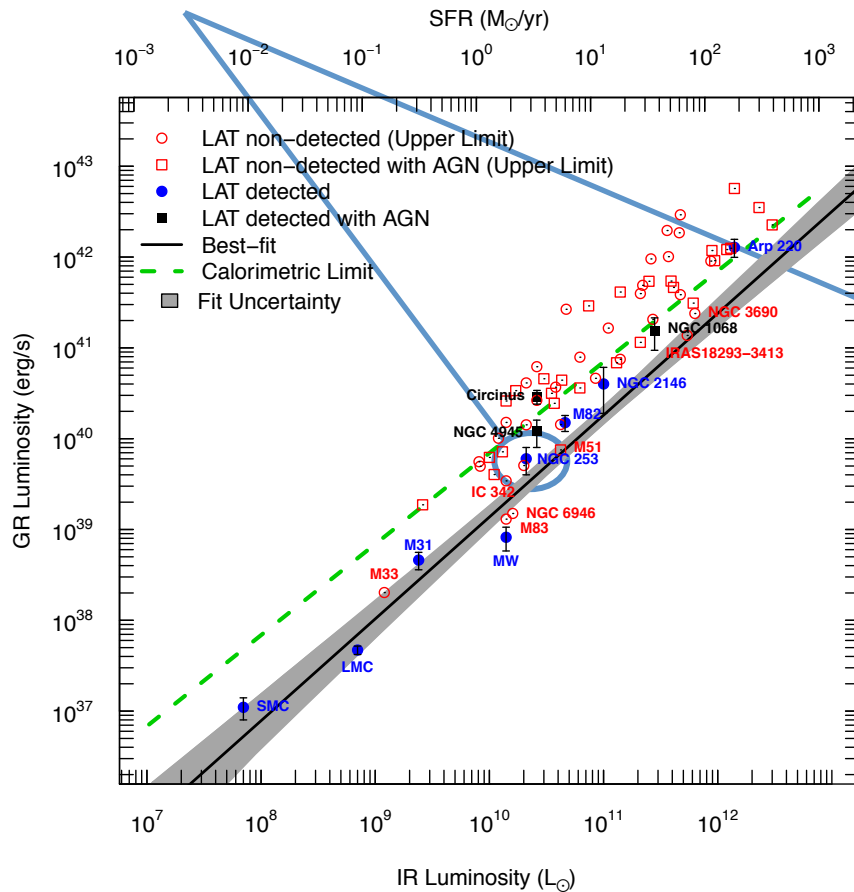
- Calorimetric fraction estimate
→ How much of the available CR power goes into pion production?
- Fraction of particles able to do pion production:

$$f_{\text{cal}} = \frac{L_{\pi}}{L_{\text{CR}}(> E_{\pi}^{\text{th.}})} \approx 0.3 \left(\frac{0.7}{f_{\pi}} \right) \left(\frac{L_{\gamma}}{10^{40} \text{ergs}^{-1}} \right) \left(\frac{2 \times 10^{41} \text{ergs}^{-1}}{L_{\text{CR}}} \right)$$

$$f_{\text{cal}} \approx 0.1 - 1$$

Gamma-Ray/Radio/Infrared Correlation

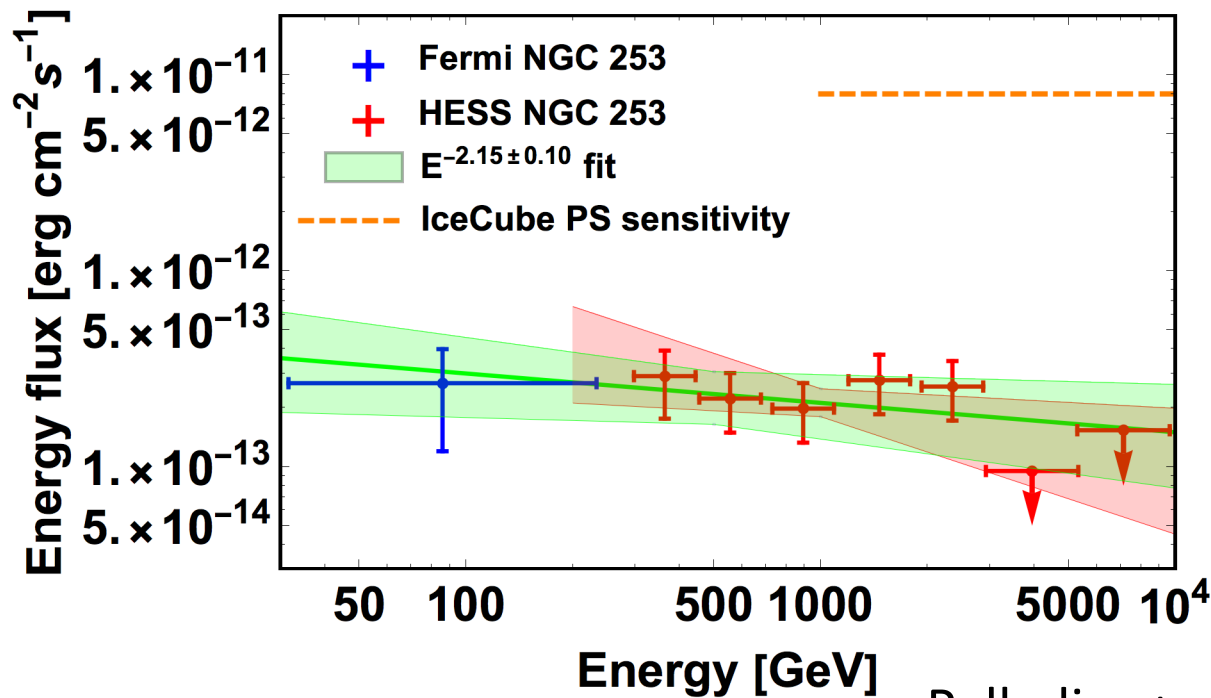
NGC 253



Rojas-Bravo & Miguel Araya,
MNRAS, 463 (2016)

Ackermann+, ApJ, 755 (2012)

Neutrinos from NGC 253



Palladino+, JCAP 1909 (2019) 004

$$L_{\gamma}^{0.1-100 \text{ GeV}} \approx 10^{40} \text{ erg s}^{-1}$$

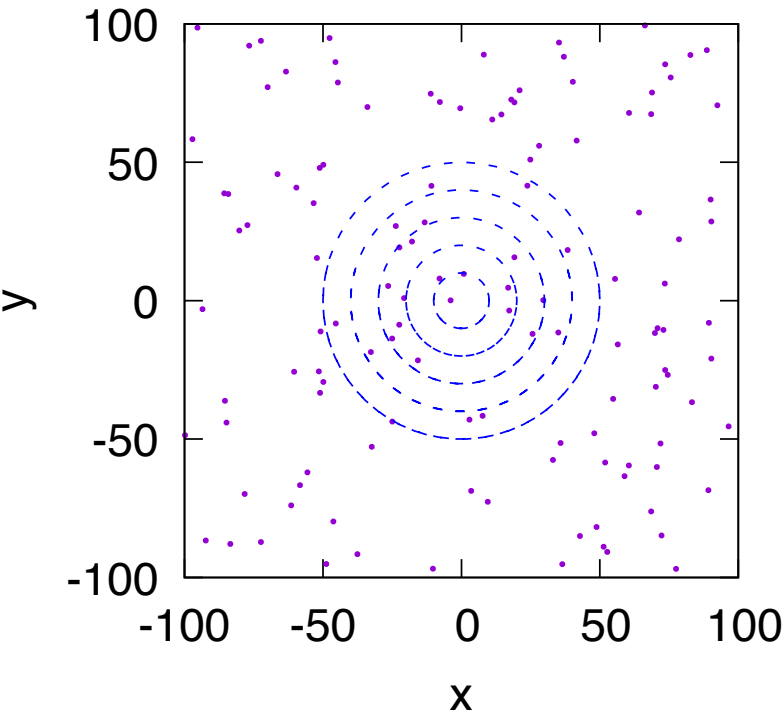
$$\rho_0 \approx 10^{-3} \text{ Mpc}^{-3}$$

Gruppioni+, MNRAS 432 (2013)

$$\rho_0 L_{\gamma}^{0.1-100} = 2 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$$

Scaling this Result Up

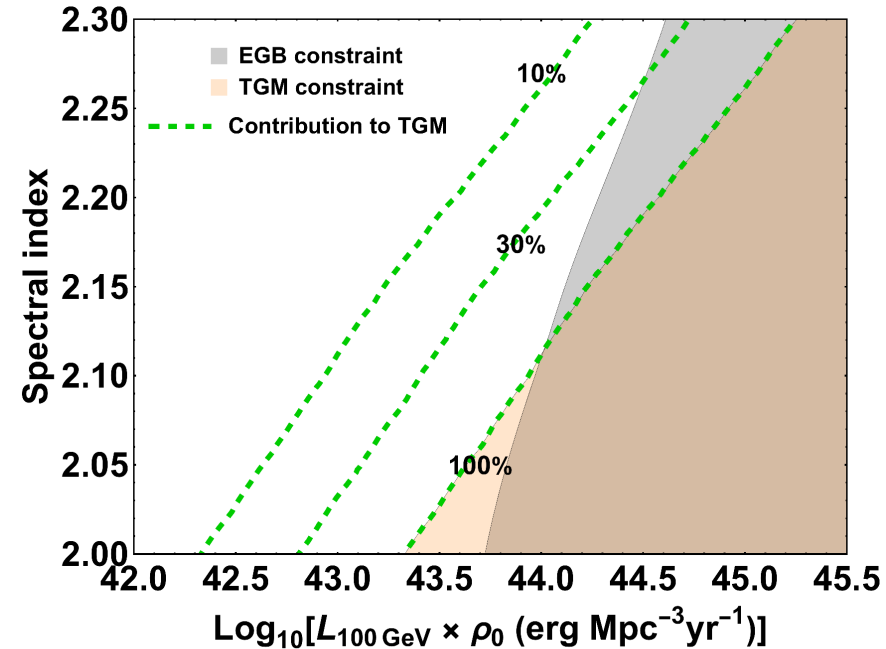
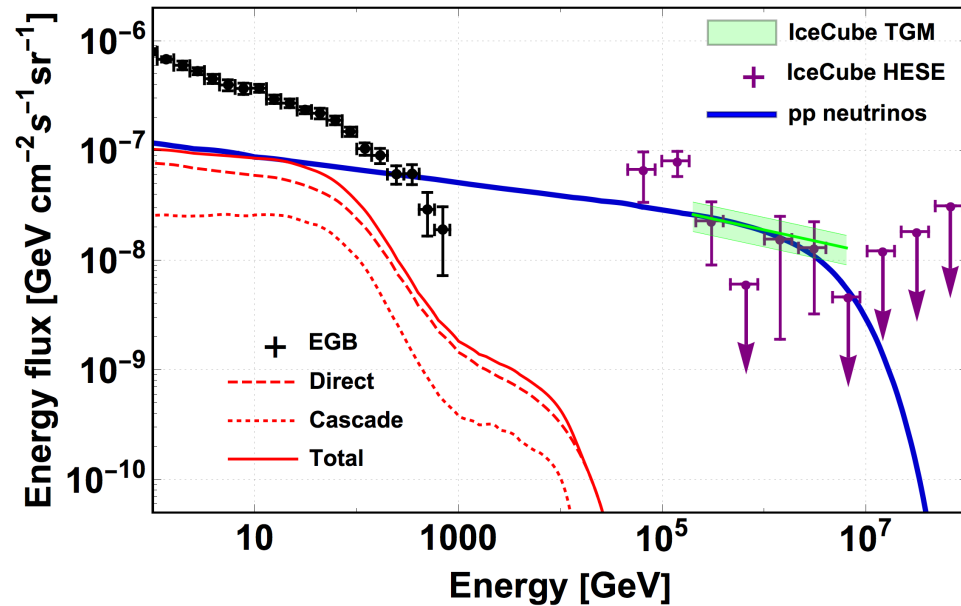
$$\frac{d\Phi_\nu(E)}{dE} = \int dz \frac{\rho(z)}{H(z)} \frac{3}{2} \frac{d\phi_\gamma}{dE}(E(1+z))$$



$$\begin{aligned} \frac{d\Phi_\nu}{dE} &\approx \left(\frac{r_{z=1}}{r_0} \right) \Phi_0 \cdot \text{SFR}(z=1) \\ &\approx (4000 - 5000) \Phi_0 \end{aligned}$$

Neutrinos from the Ensemble of Starburst Galaxies

Palladino+, JCAP 1909 (2019) 004



α	E_{cut}^*	NGC 253 $\rho_0(\alpha)$	ARP 220 $\rho_0(\alpha)$	Contribution to total EGB	Fermi coll. [41]	Tension with	
						Lisanti et al. [42]	Zechlin et al. [43]
1.9	3.2	7.7×10^{-5}	5.1×10^{-7}	6%	no	no	no
2.0	4.1	2.3×10^{-4}	1.6×10^{-6}	11%	no	no	no
2.1	5.1	7.9×10^{-4}	5.3×10^{-6}	25%	0.8σ	no	0.3σ
2.12	5.3	1.0×10^{-3}	6.7×10^{-6}	28%	1σ	no	0.5σ
2.2	6.3	2.8×10^{-3}	1.8×10^{-5}	50%	2.6σ	2.1σ	1.7σ
2.3	7.8	1.1×10^{-2}	7.2×10^{-5}	100%	6.9σ	8.7σ	4.8σ

DESY.

(compatible with level estimated in Ackermann+, ApJ 755 (2012) 164
+ constraint provided by Bechtol+ Astrophys.J. 836 (2017) 47)

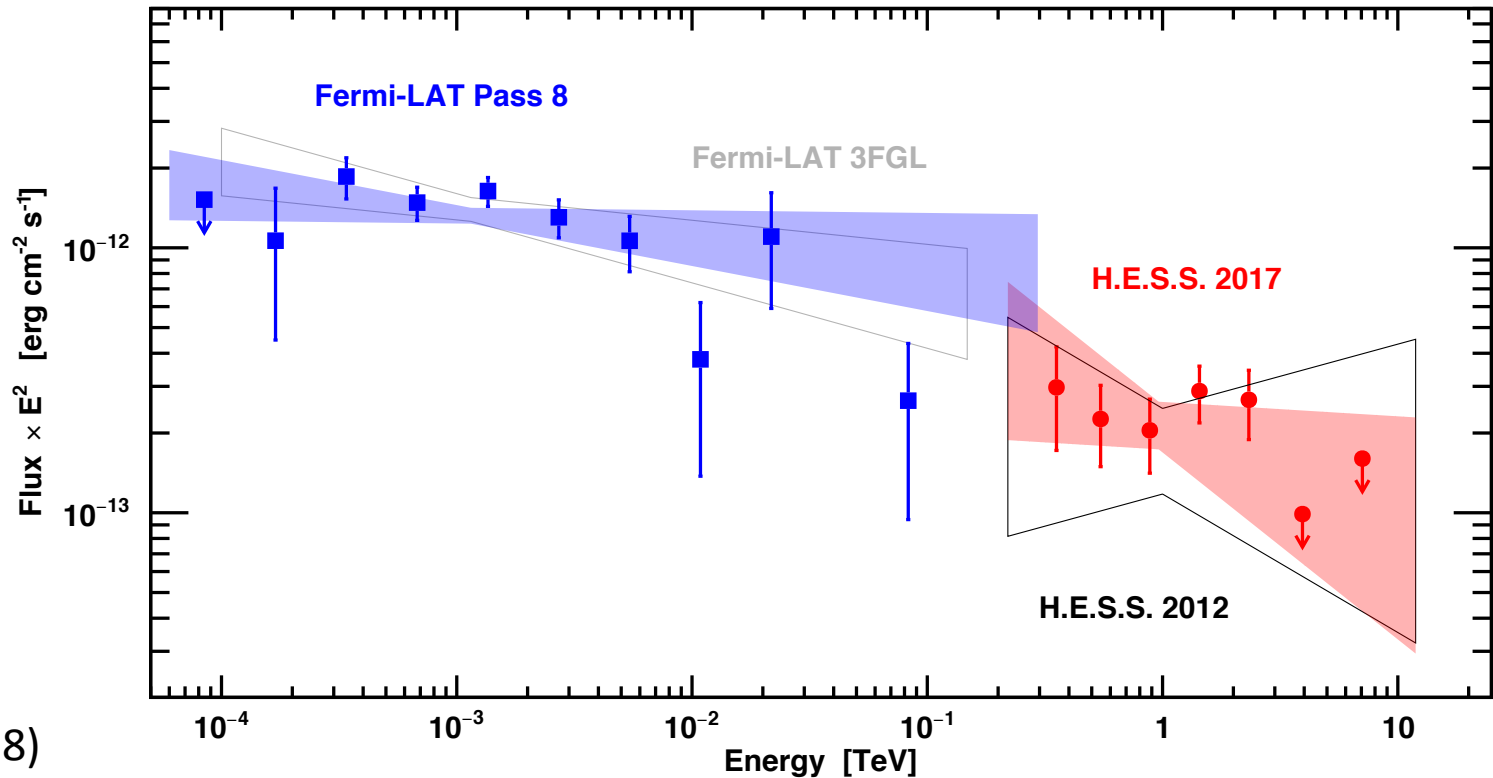
Summary on Starbursts

- Starburst galaxies are particularly dusty galaxies thanks to enhanced activity of massive stars, giving rise to larger IR emission
- Their gamma-ray emission is believed hadronic (pp) in origin, emanating from the galactic center region, with the emission region being presently unresolved.
- Their gamma-ray emission appears to grow faster than linearly with their IR emission.
- Although individually these are weak sources, collectively they can account for a significant fraction of the residual diffuse gamma-ray and neutrino backgrounds

NGC 253: Gamma-Ray Spectrum

Gamma-Ray Spectral Coverage-
very good energy information

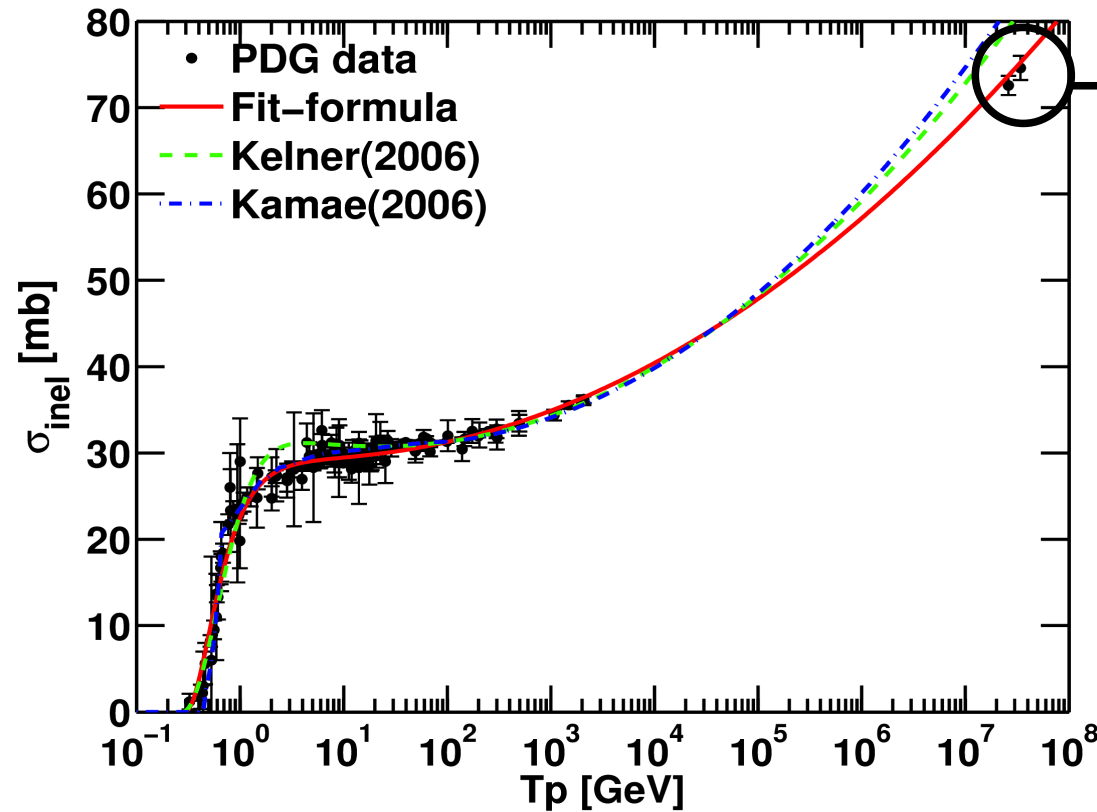
$$L_{\gamma}(\text{GeV}) \approx 10^{40} \text{ erg s}^{-1}$$



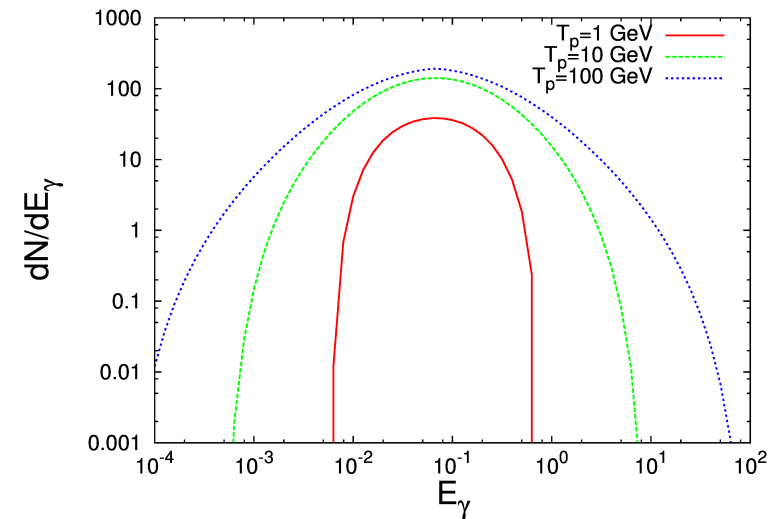
A&A 617, A73 (2018)

Do cosmic ray protons dump all their energy within the
source, or are some fraction of them able to escape?

NGC 253: Hadronic Gamma-Ray Emission



New TOTEM
data points



Kafexhiu+ Phys.Rev. D90 (2014)

$$\sigma_{\text{inel}} = \left(30.7 - 0.96 \log \left(\frac{T_p}{T_p^{\text{th}}} \right) + 0.18 \log^2 \left(\frac{T_p}{T_p^{\text{th}}} \right) \right) \times \left[1 - \left(\frac{T_p^{\text{th}}}{T_p} \right)^{1.9} \right]^3 \text{ mb}$$

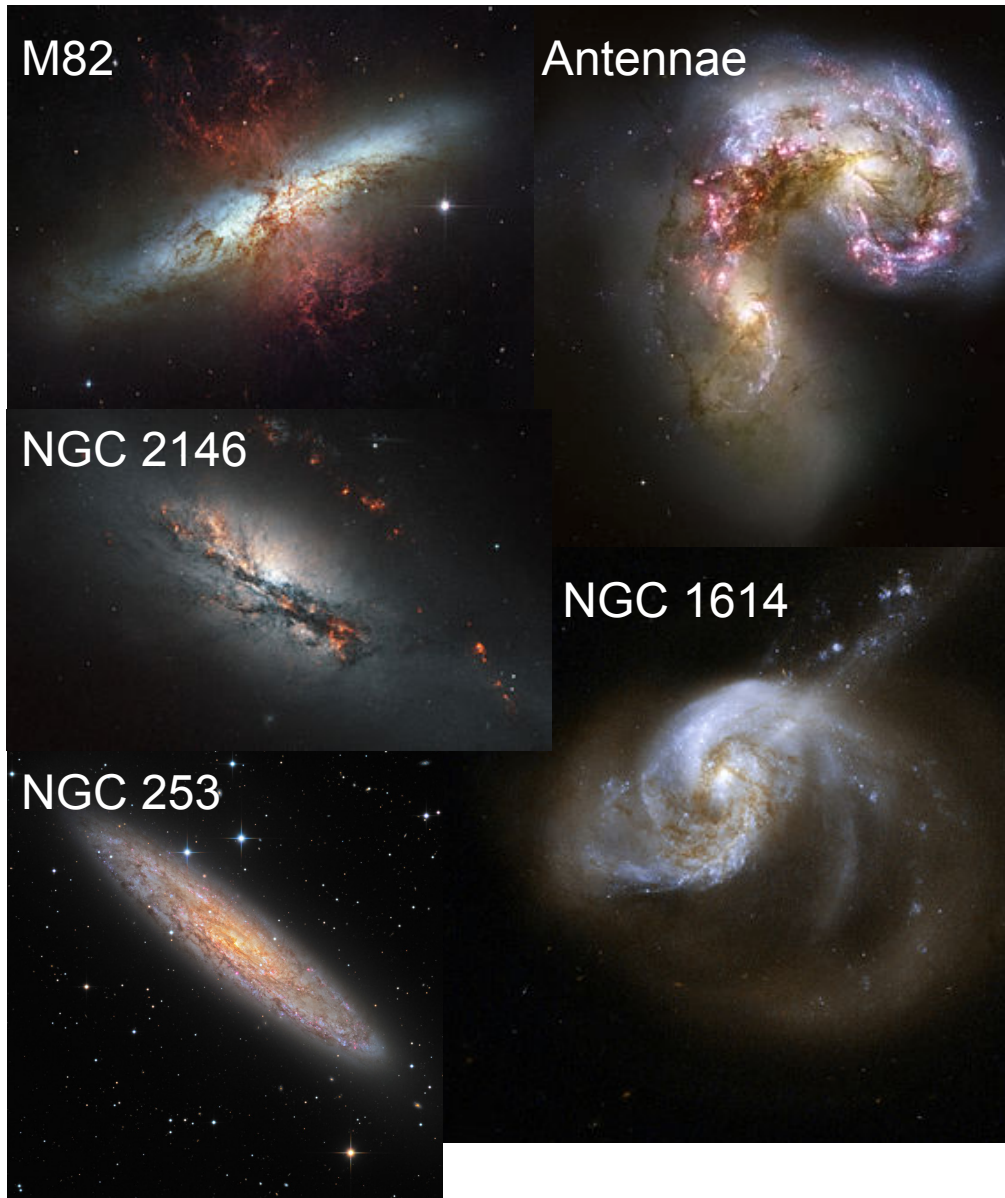
Starburst Galaxies: General

- Definitions:

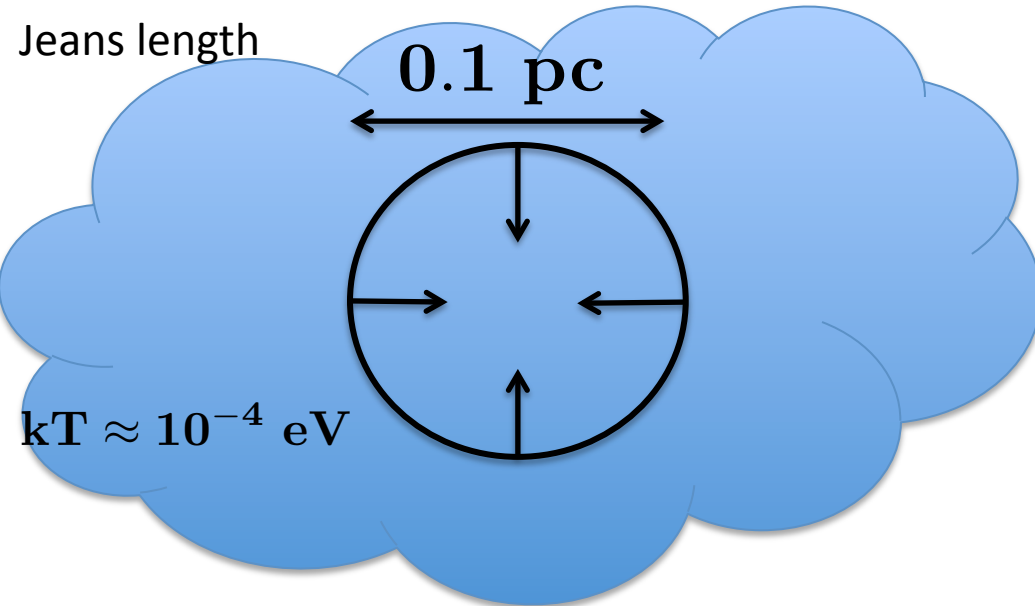
- High SFR compared to “normal” spiral galaxies.
 - $> 100 \times$ SFR of MW
- Undergoing high SFR compared to galaxy’s long term average.
 - High sSFR

- Bottom line: high & highly-variable SFRs.

- Short timescales ($\tau \lesssim 10^8$ yr)
- 2% of massive galaxies are bursty
- 10% of total SFRD



Star Formation is Bursty



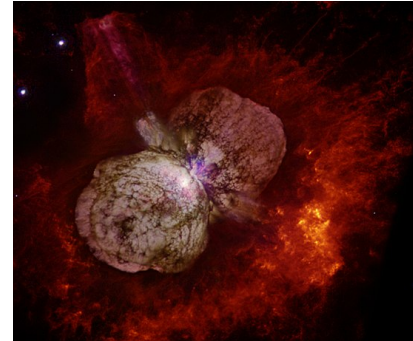
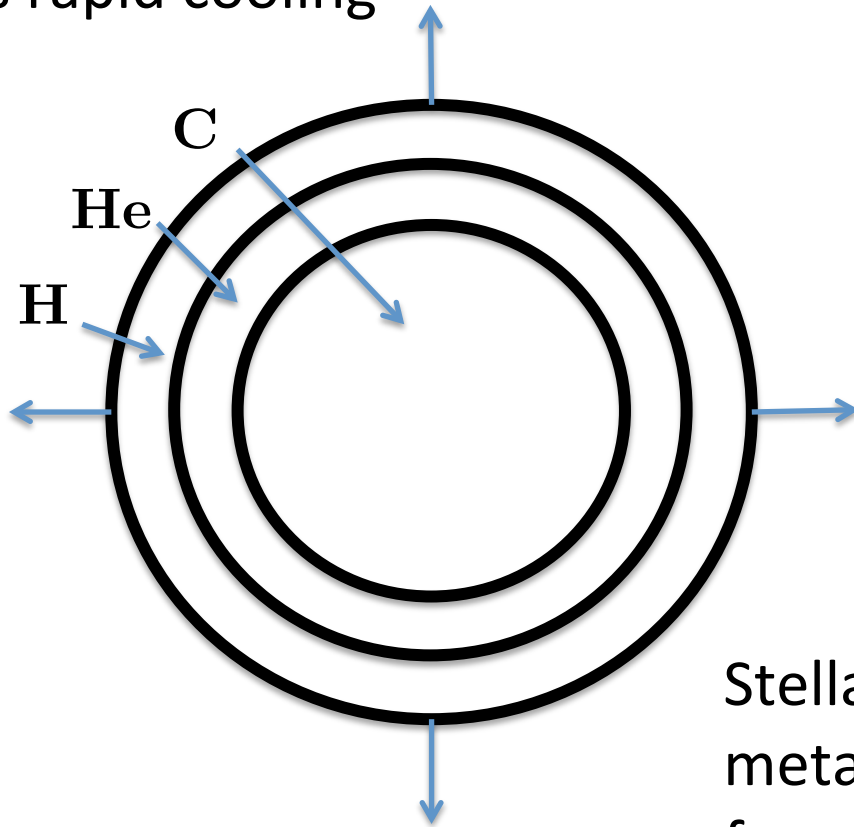
$$t_{\text{ff}} \approx \left(\frac{r^3}{GM} \right)^{1/2} \\ \approx \left(\frac{10^4 \text{ cm}^{-3}}{n} \right)^{1/2} \text{ Myr}$$

$$\beta_{\text{th}} = \left(\frac{kT}{m_p c^2} \right)^{1/2} \\ \approx 10^{-6.5}$$

$$t_{\text{sc}} = \frac{r}{v_{\text{th}}} \\ \approx \left(\frac{r}{0.1 \text{ pc}} \right) \left(\frac{30 \text{ K}}{T} \right)^{1/2} \text{ Myr}$$

Dust Production?

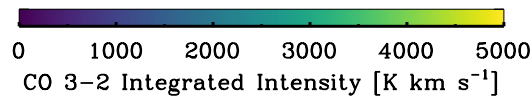
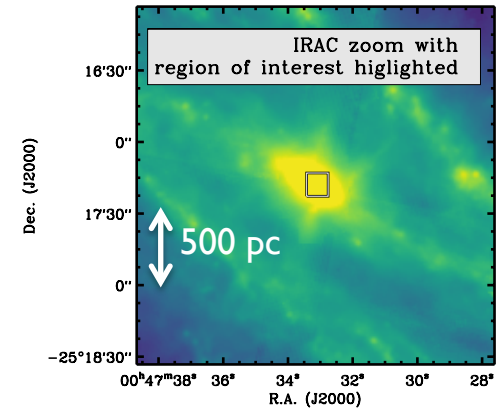
Adiabatic cooling of the outflow leads to its rapid cooling



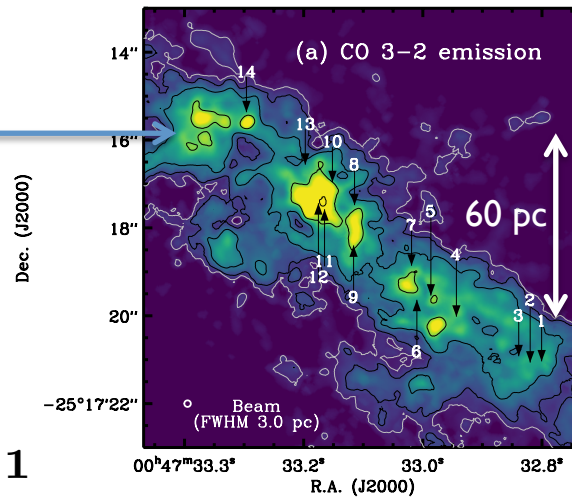
$$kT_{\text{sub}} \approx 0.1 \text{ eV}$$

Stellar winds are a major polluter of metals in molecular clouds to feed dust formation

Small Scale Thermal Emission



Super Star Clusters

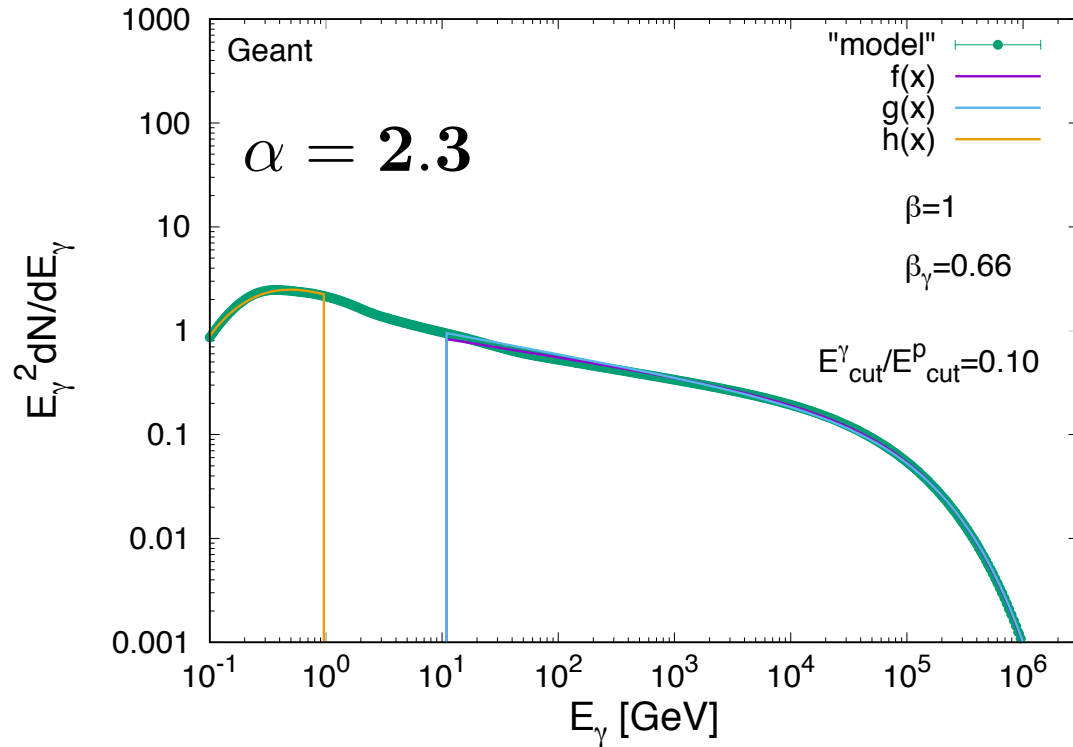


$$L_{\gamma}^{\text{IR}} \approx 3 \times 10^{43} \text{ erg s}^{-1}$$

A. Leroy+ 2018

NGC 253: Hadronic Gamma-Ray Emission

$$\Phi_{\gamma}(E_{\gamma}) = 4\pi n_{\text{H}} \int \frac{d\sigma}{dE_{\gamma}}(p_p, E_{\gamma}) J(p_p) dp_p$$



$$J_p(p_p) = \frac{A}{p_p^{\alpha}} \exp \left[- \left(\frac{p_p}{p_p^{\text{max}}} \right)^{\beta} \right]$$

NGC 253: Gamma-Ray Perspective

- Energy Loss Timescales

$$t_{pp} = \left(\frac{1}{cn_p \sigma_{pp} K_{pp}} \right)$$

$$t_e(\mathbf{E}_e) = \frac{1}{(4/3)cn_\gamma \sigma_T b}$$

$$b = E_e E_\gamma / m_e^2$$



$$t_e(\mathbf{E}_e) = \frac{m_e^2}{(4/3)cE_e \sigma_T U_{\gamma/B}}$$

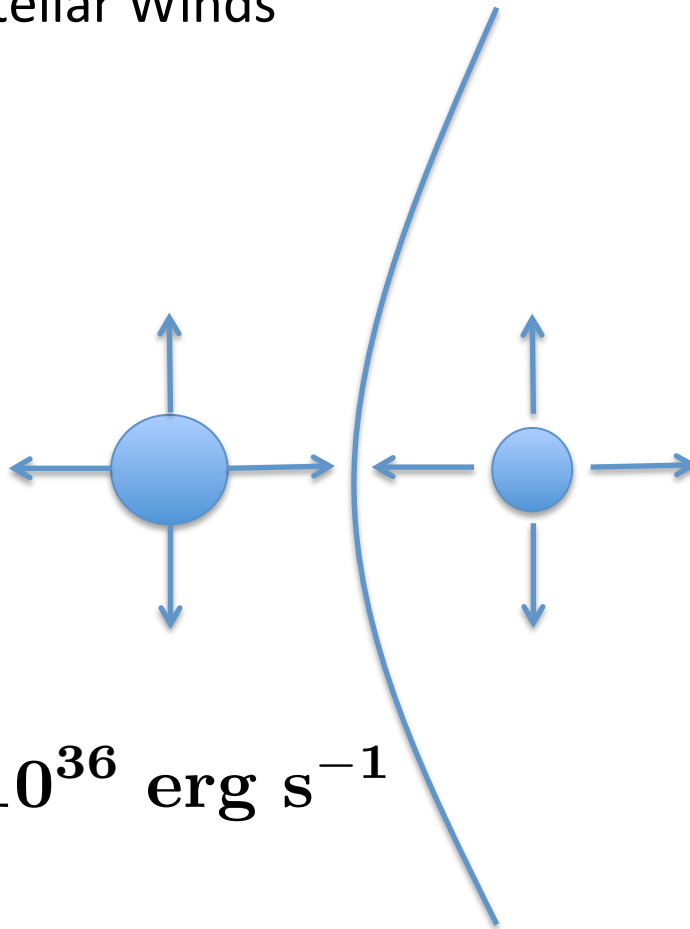
III. Starburst Non-Thermal Particle Accelerators

Particle Acceleration in Starburst Systems

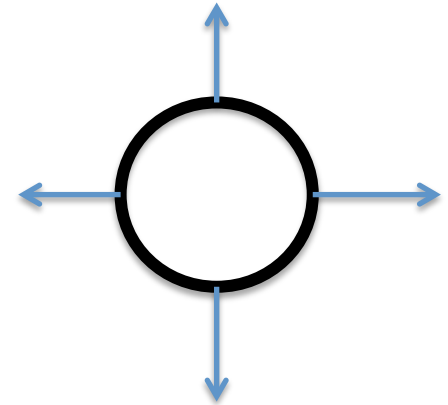
What acceleration source/process is at play?

1) Colliding Stellar Winds

2) SNR blastwave



$$L_{\text{wind}} \approx 10^{36} \text{ erg s}^{-1}$$

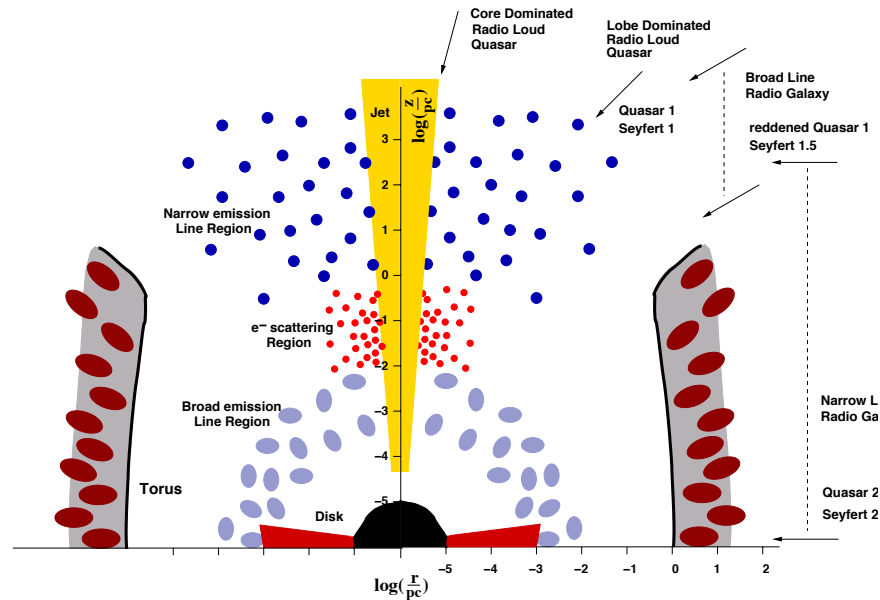


$$E_{\text{KE}} \approx 10^{51}$$

Particle Acceleration in Starburst Systems

What acceleration source/process is at play?

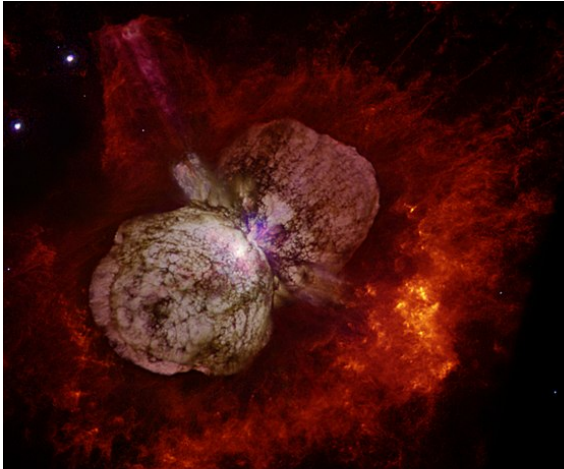
3) AGN



$$L_{\text{wind}} \approx 3 \times 10^{40} \text{ erg s}^{-1}$$

Particle Acceleration in Stellar Winds

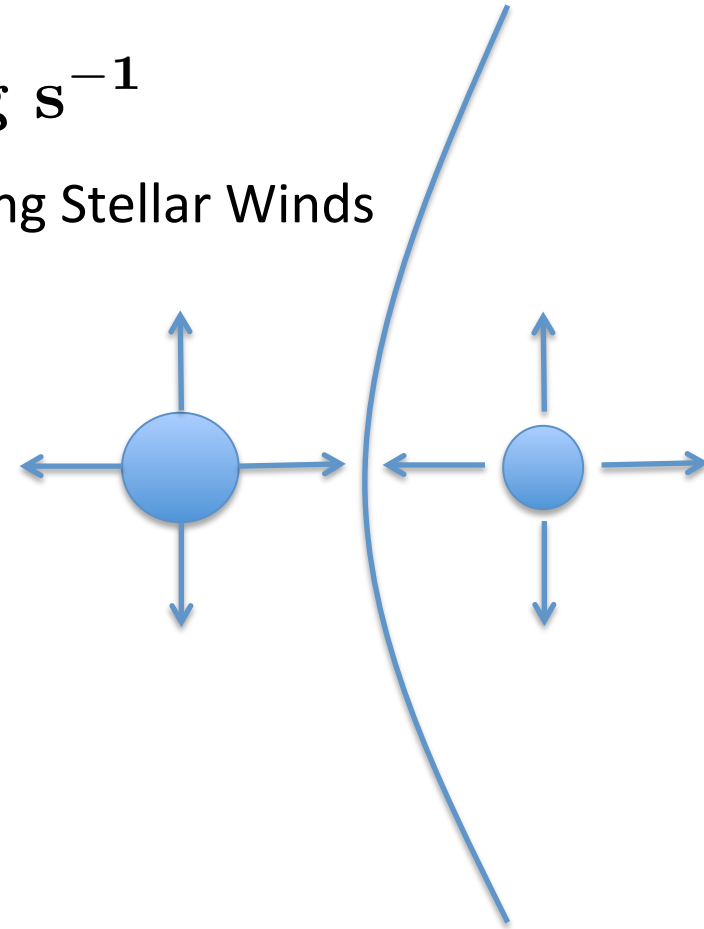
Hubble Image



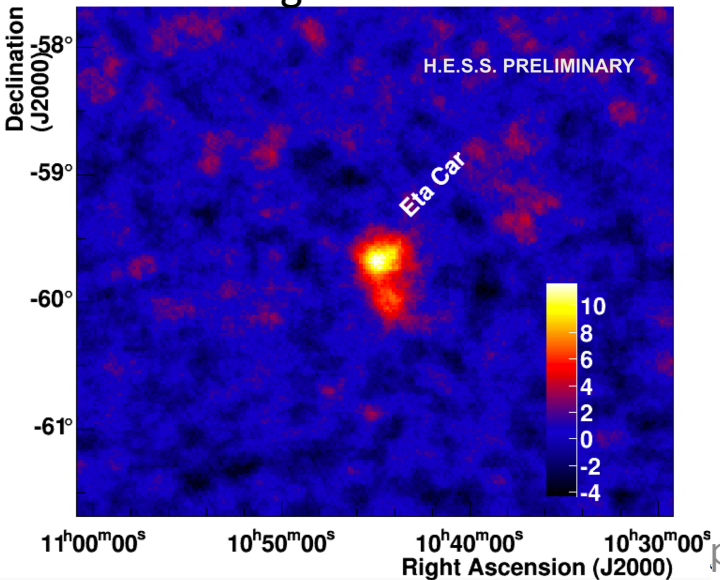
$$L_{\gamma}^{\text{th.}} \approx 10^{39} \text{ erg s}^{-1}$$

$$L_{\text{wind}} \approx 10^{36} \text{ erg s}^{-1}$$

2) Colliding Stellar Winds



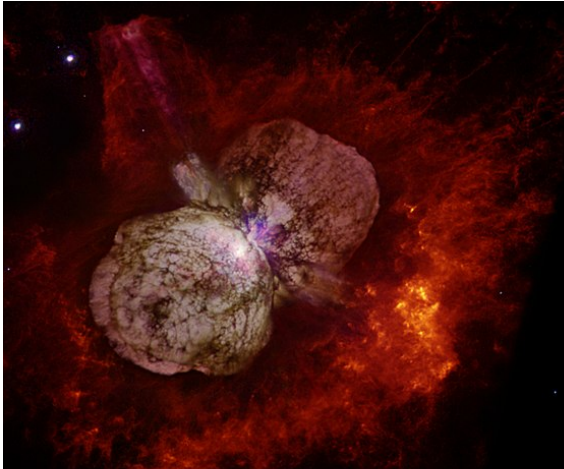
HESS Image



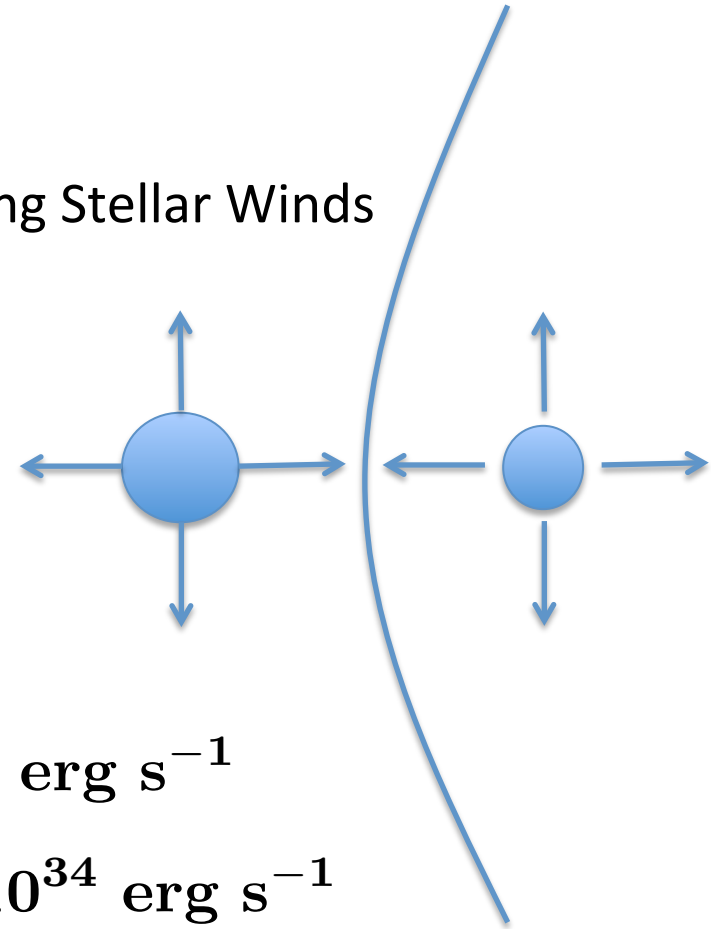
[Note- Eta Car is not a Galactic Center Object]

Particle Acceleration in Stellar Winds

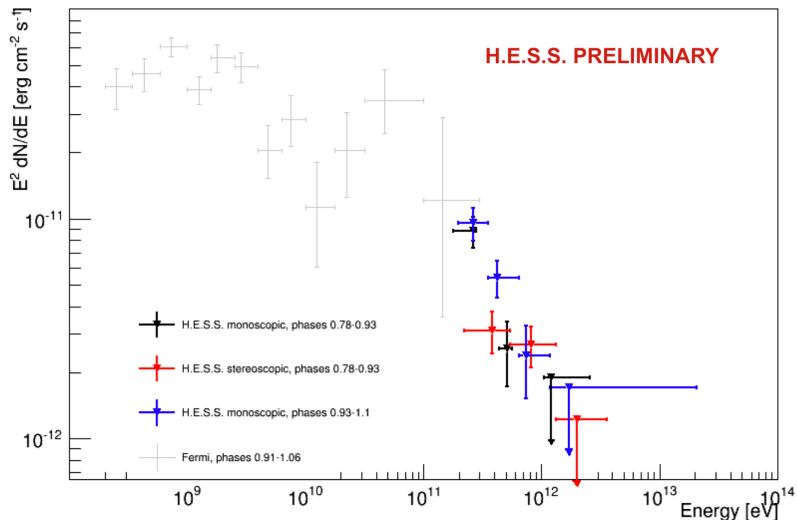
Hubble Image



2) Colliding Stellar Winds



Spectrum



$$L_{\text{wind}} \approx 10^{36} \text{ erg s}^{-1}$$

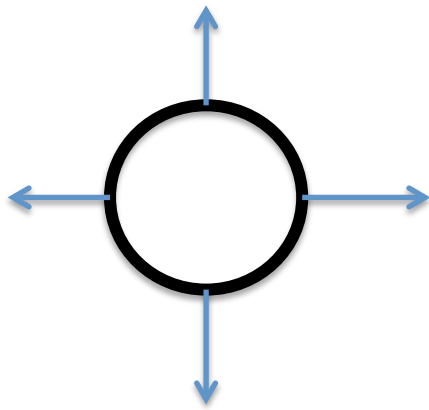
$$L_{\gamma}^{\text{GeV}} \approx 3 \times 10^{34} \text{ erg s}^{-1}$$

Close-ish to calorimetric regime

Particle Acceleration in Supernova

What acceleration source/process is at play?

1) SNR blastwave

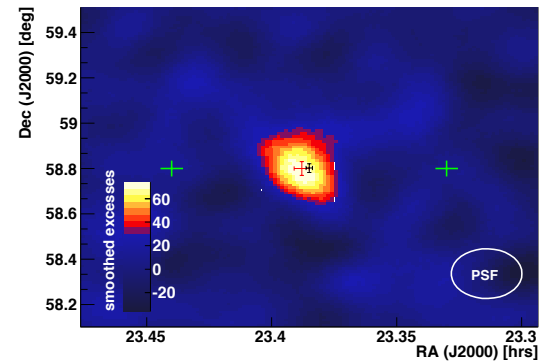


$$E_{KE} \approx 10^{51}$$

Herschel/Hubble Image



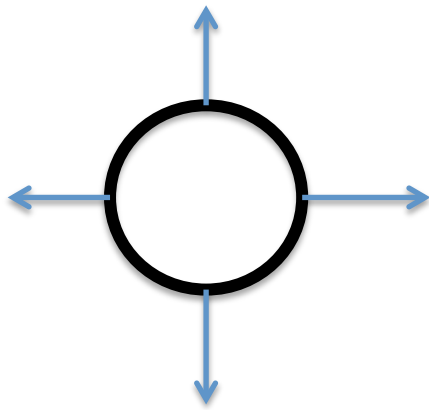
MAGIC Image



Particle Acceleration in Supernova

What acceleration source/process is at play?

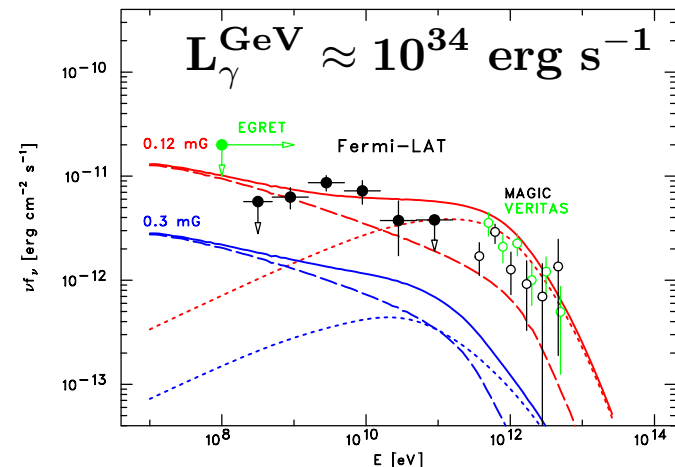
1) SNR blastwave



Herschel/Hubble Image



Spectrum

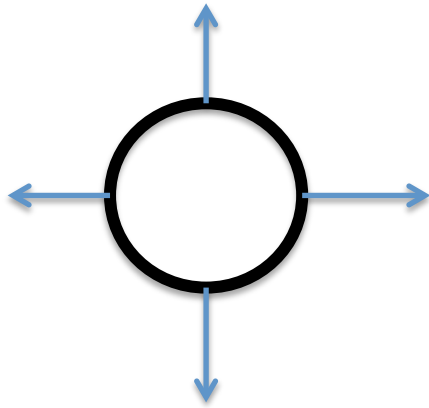


$$E_{KE} \approx 10^{51}$$

Particle Acceleration in Supernova

What acceleration source/process is at play?

1) SNR shock



$$E_{KE} \approx 10^{51}$$

Herschel/Hubble Image

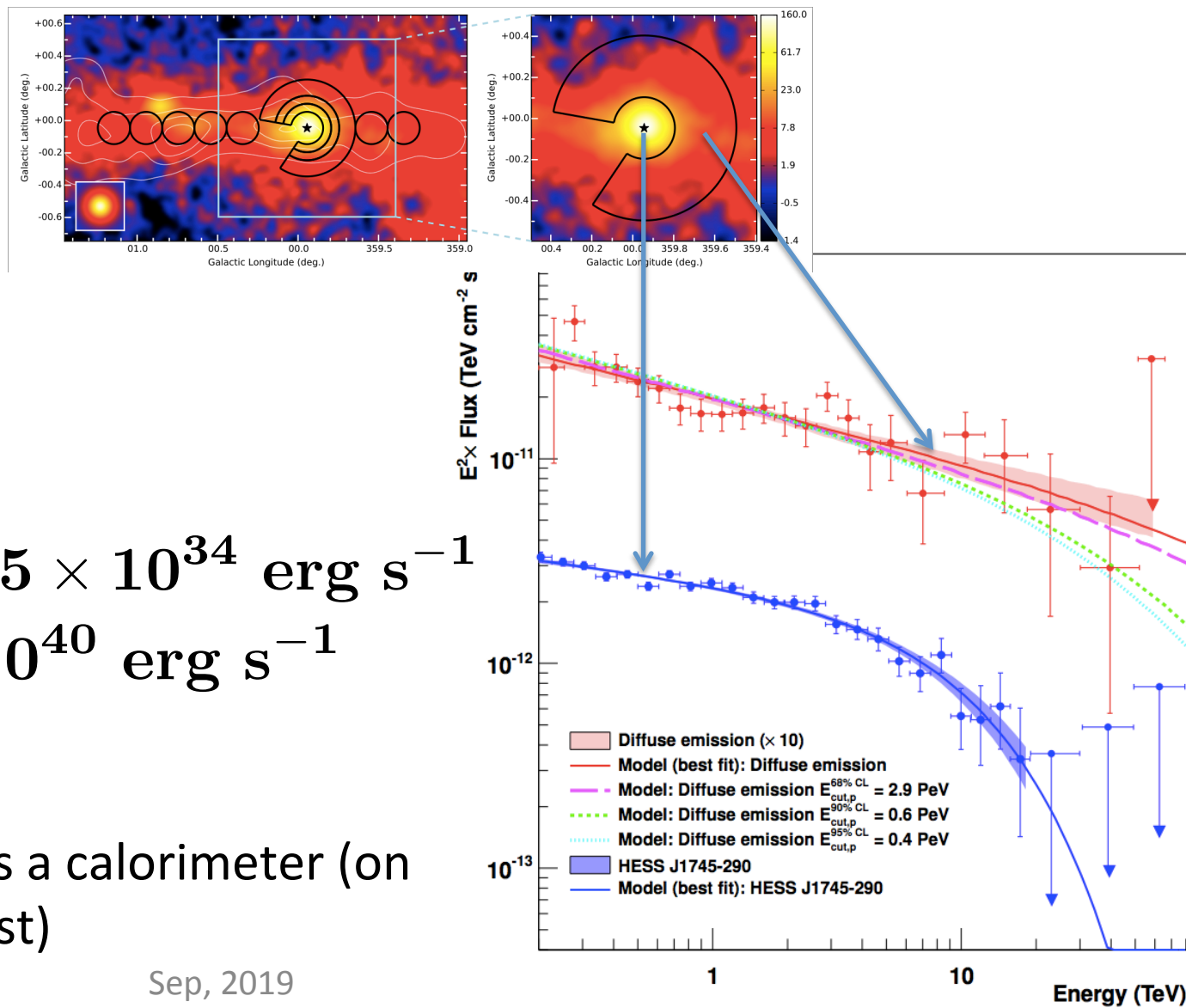


Spectrum

$$L_{\gamma}^{\text{GeV}} \approx 10^{34} \text{ erg s}^{-1}$$

Note- not acting as a calorimeter (on source scales at least)

Particle Acceleration by AGN

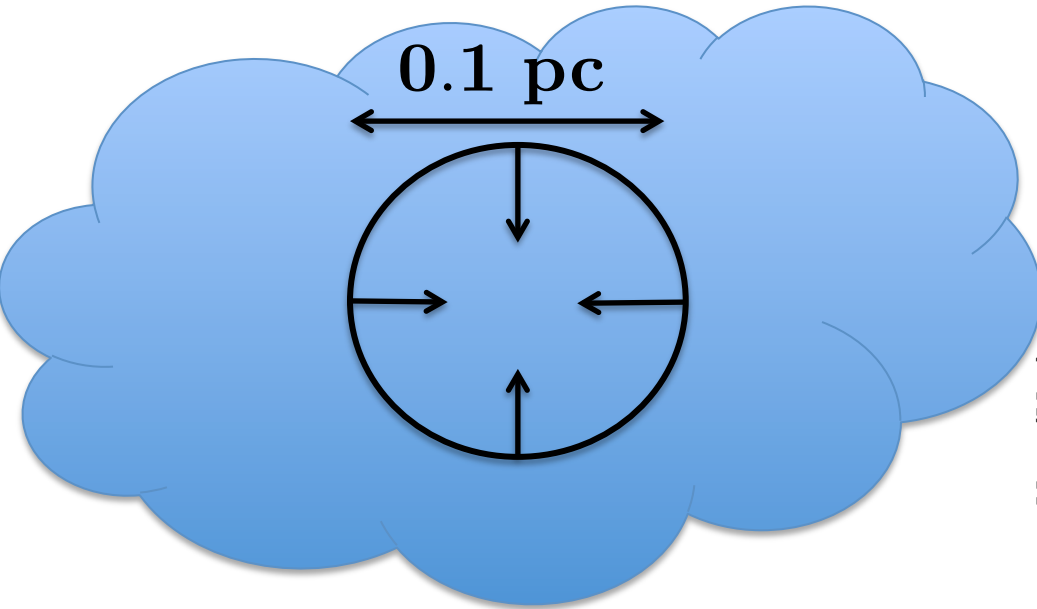


$$L_{\gamma}(1 \text{ TeV}) \approx 5 \times 10^{34} \text{ erg s}^{-1}$$

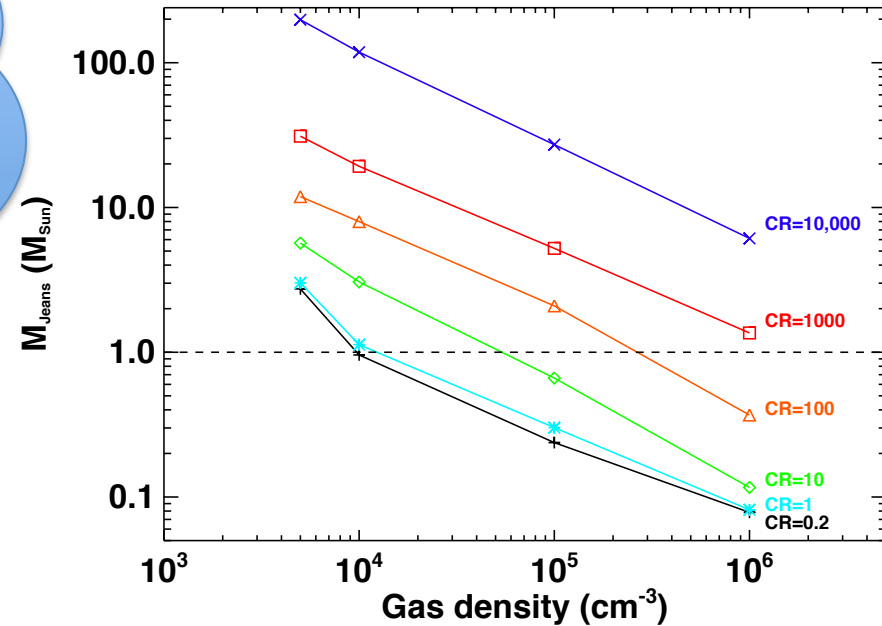
$$L_{\text{wind}} \approx 3 \times 10^{40} \text{ erg s}^{-1}$$

Note- not acting as a calorimeter (on these scales at least)

Effect of Cosmic Rays on Star Formation?

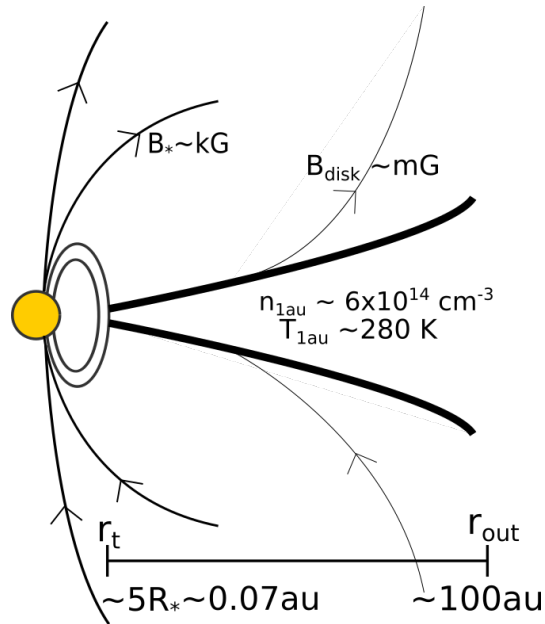


Some suggestion that CRs play a role in heating MCs and therefore biasing star formation towards massive stars

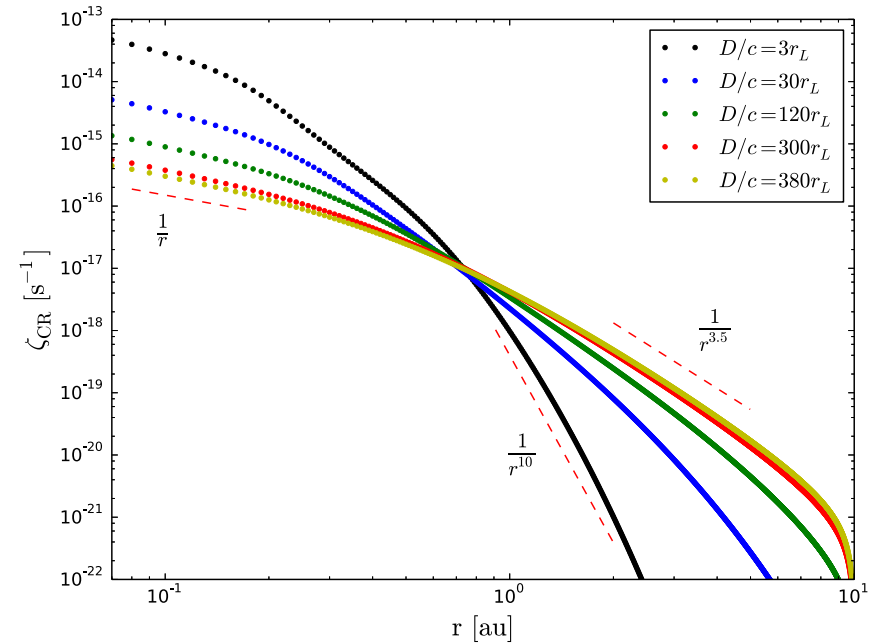


Papadopoulos+ MNRAS, 414 (2011)

Effect of Cosmic Rays on Star Formation?



Rodgers-Lee+ MNRAS 472 (2017)

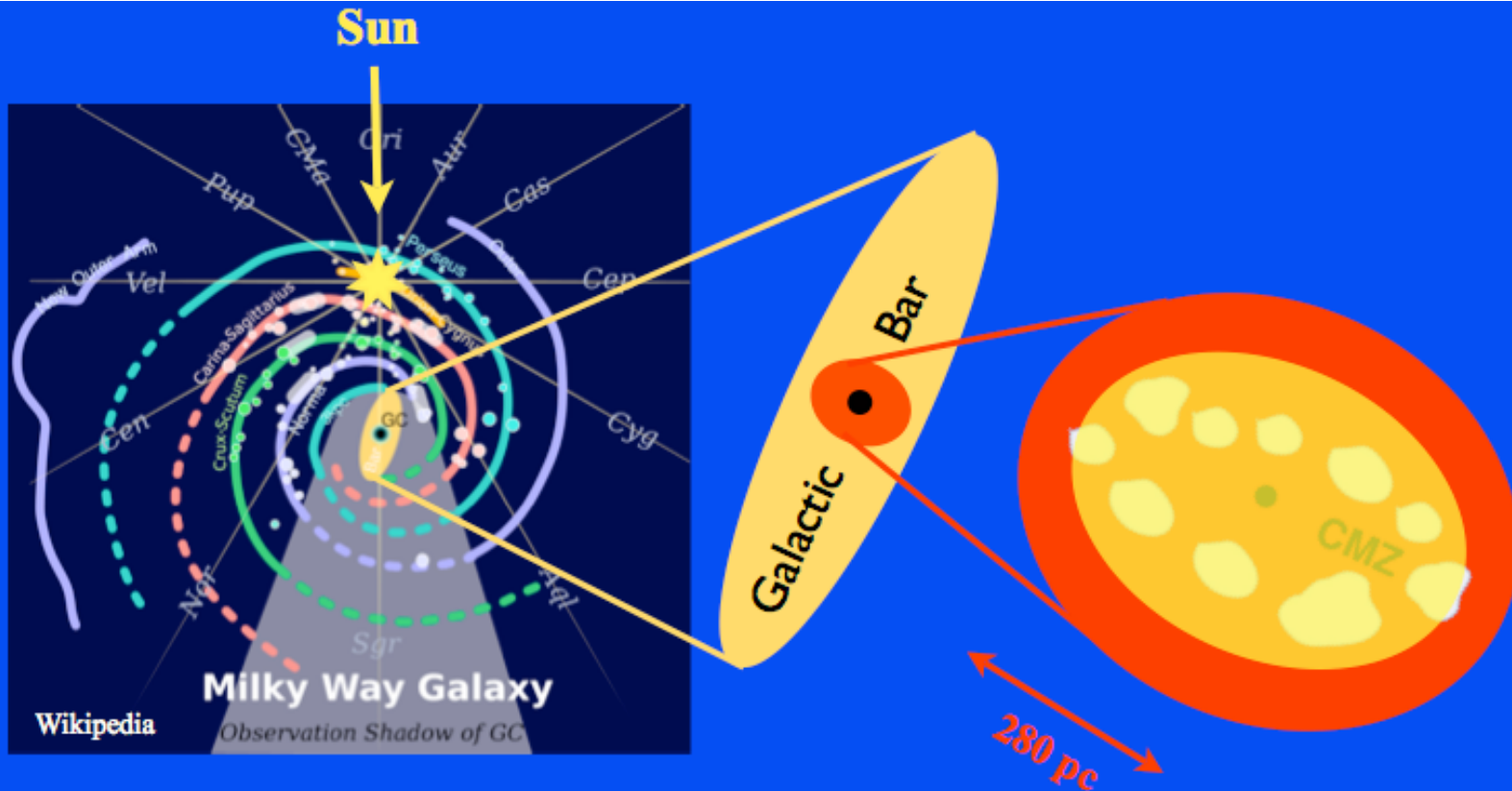


CRs are also a very effective ionisation agent at large radii, and may provide an important role in ionising the YSO accretion disks

$$\zeta_{\text{CR}}(r, z) = 2.2 \times 10^{-18} \text{ s}^{-1} \frac{n_{\text{CR}}(r, z)}{4 \times 10^{-10} \text{ cm}^{-3}}$$

IV. Starburst Galaxy Outflows

Central Molecular Zones



Milky Way Bar

Binney et al. 1991

Englmaier & Gerhard 1999

Bissantz et al. 2003

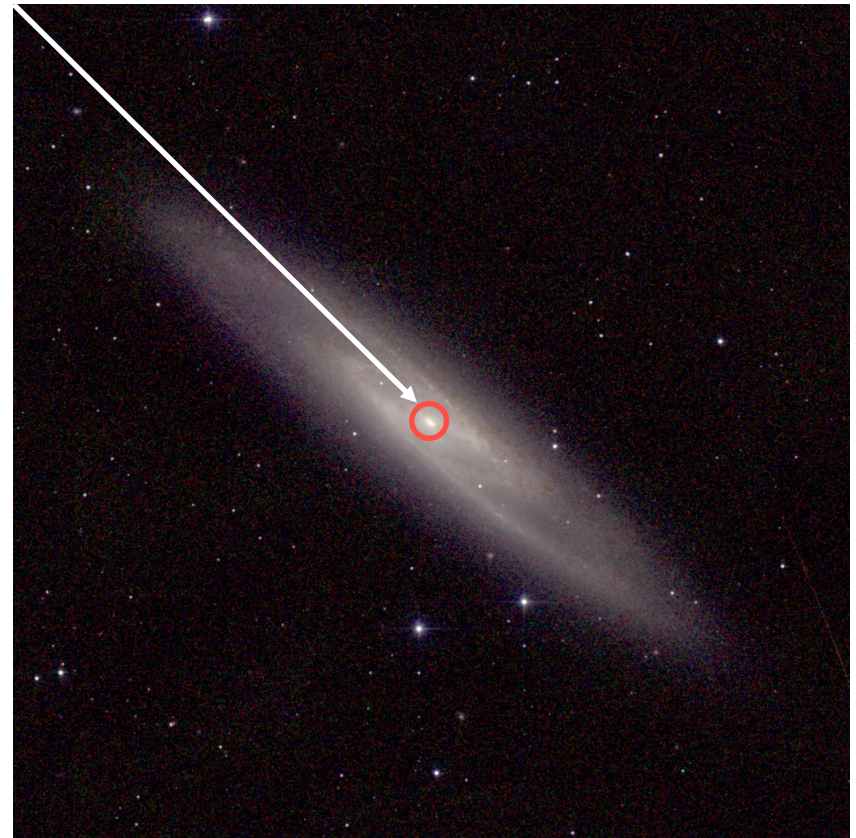
Rattenbury et al. 2007

Central Molecular Zones

- Much of the GC' s H_2 is located in a ~ 30 million solar mass torus of gas
- The torus hosts some on-going, localized star-formation
- This seems to be a small version of the nuclear star forming rings seen in other barred spiral galaxies
- GC hosts $\sim 5\text{-}10\%$ of Galaxy' s *massive* star formation $\rightarrow$ important to Galactic star formation ecology

Central Molecular Zones

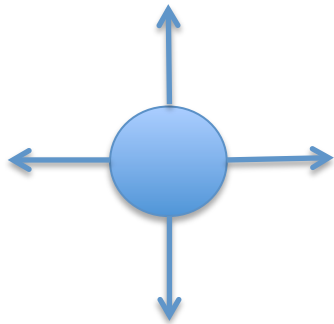
- Circumnuclear starbursts are actually common to most luminous galaxies.
- CMZs are characterized by:
 - Radius ~ 100 to 300 pc
 - Large amounts of dense molecular gas
 - Strong magnetic fields and intense radiation fields
 - Highly variable star-formation rates



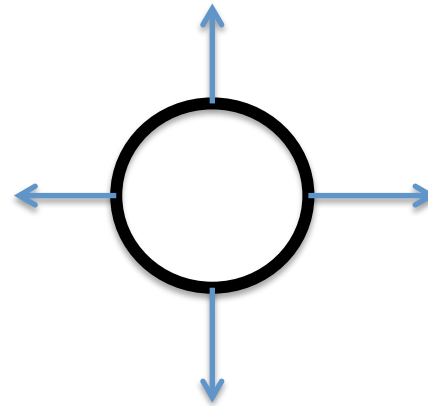
Starburst Galaxy: NGC 253

Momentum Drivers in the CMZ of NGC 253

1) Colliding Stellar Winds



2) SNR shock

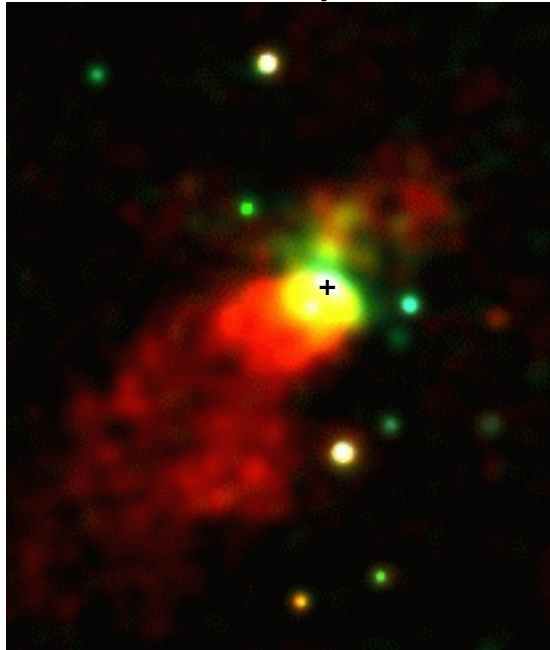


$$\langle L_{\text{wind}} \rangle \approx 10^{39} \text{ erg s}^{-1}$$

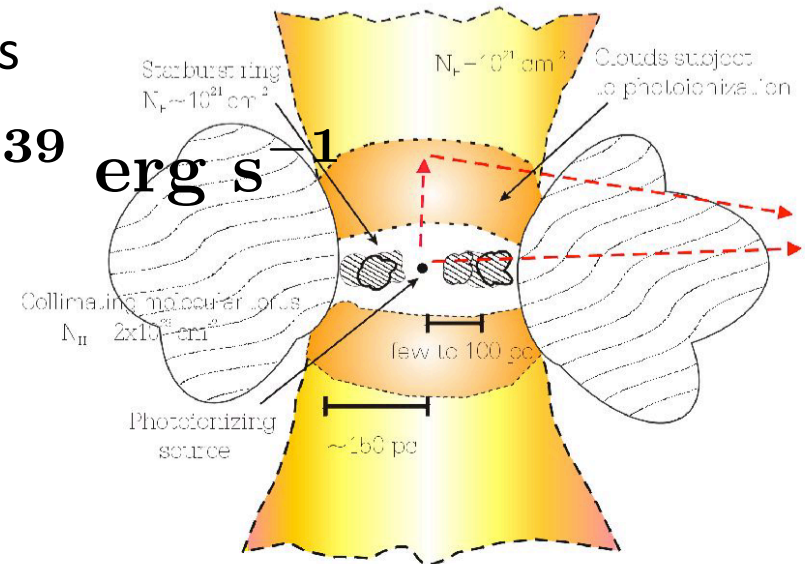
$$\langle L_{\text{SN}} \rangle \approx 10^{42} \text{ erg s}^{-1}$$

NGC 253- Galactic Center Outflow

Chandra X-ray observations of the nucleus



$$L_{\text{X-ray}} \gtrsim 10^{39} \text{ erg s}^{-1}$$



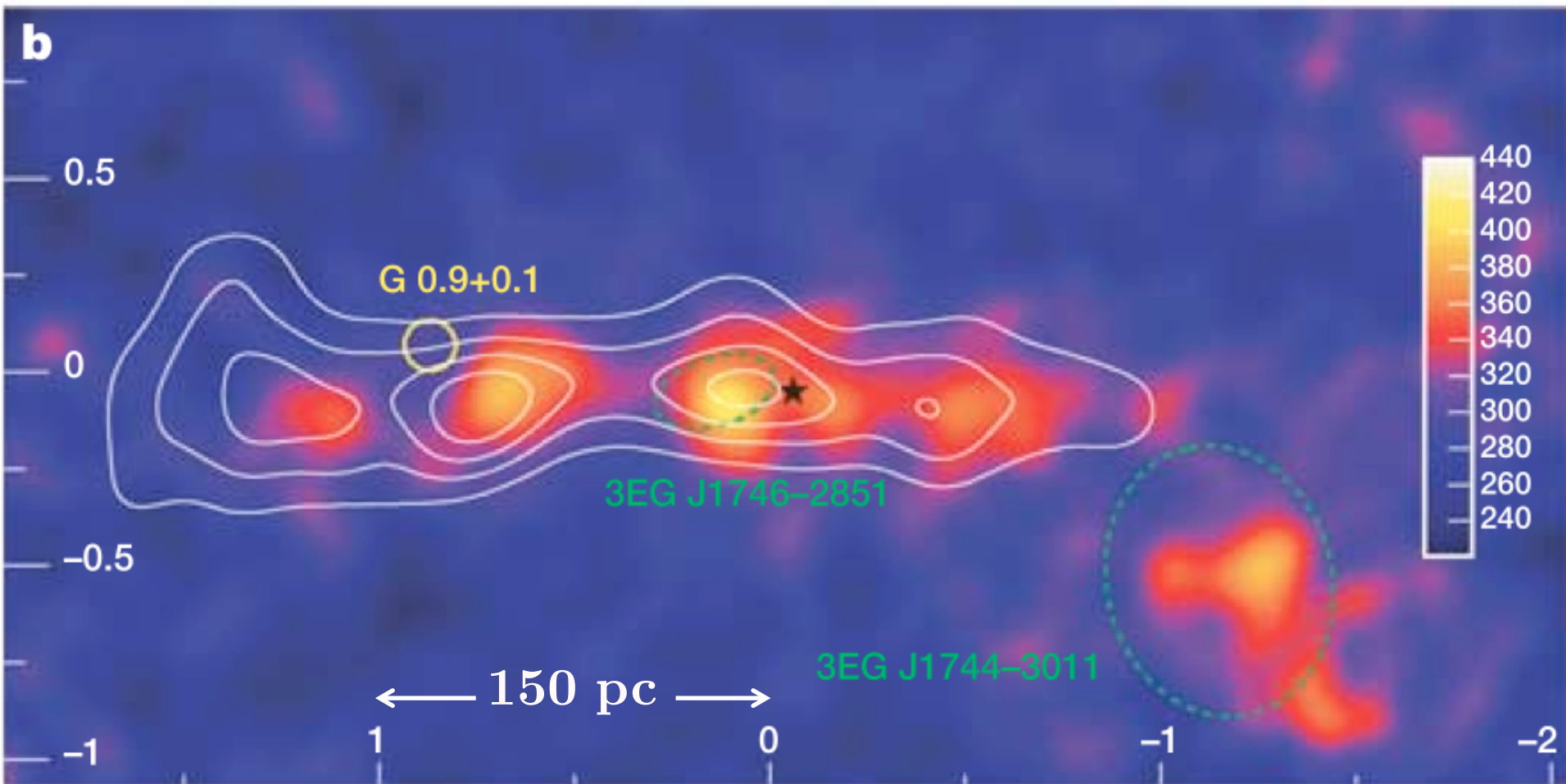
Weaver, K. +, Ap.J. 576 (2002)

1.4 kpc x 1.6 kpc

$$E_{\gamma} \approx 2 \text{ keV} \left(\frac{E_e}{20 \text{ TeV}} \right)^2 \left(\frac{B}{200 \mu\text{G}} \right)$$

$$\tau_{\text{cool}}(20 \text{ TeV}) \approx 10 \text{ yrs}$$

Milky Way- Galactic Center Outflow



$$L_{\gamma}(1 \text{ TeV}) \approx 5 \times 10^{34} \text{ erg s}^{-1}$$

DESY.

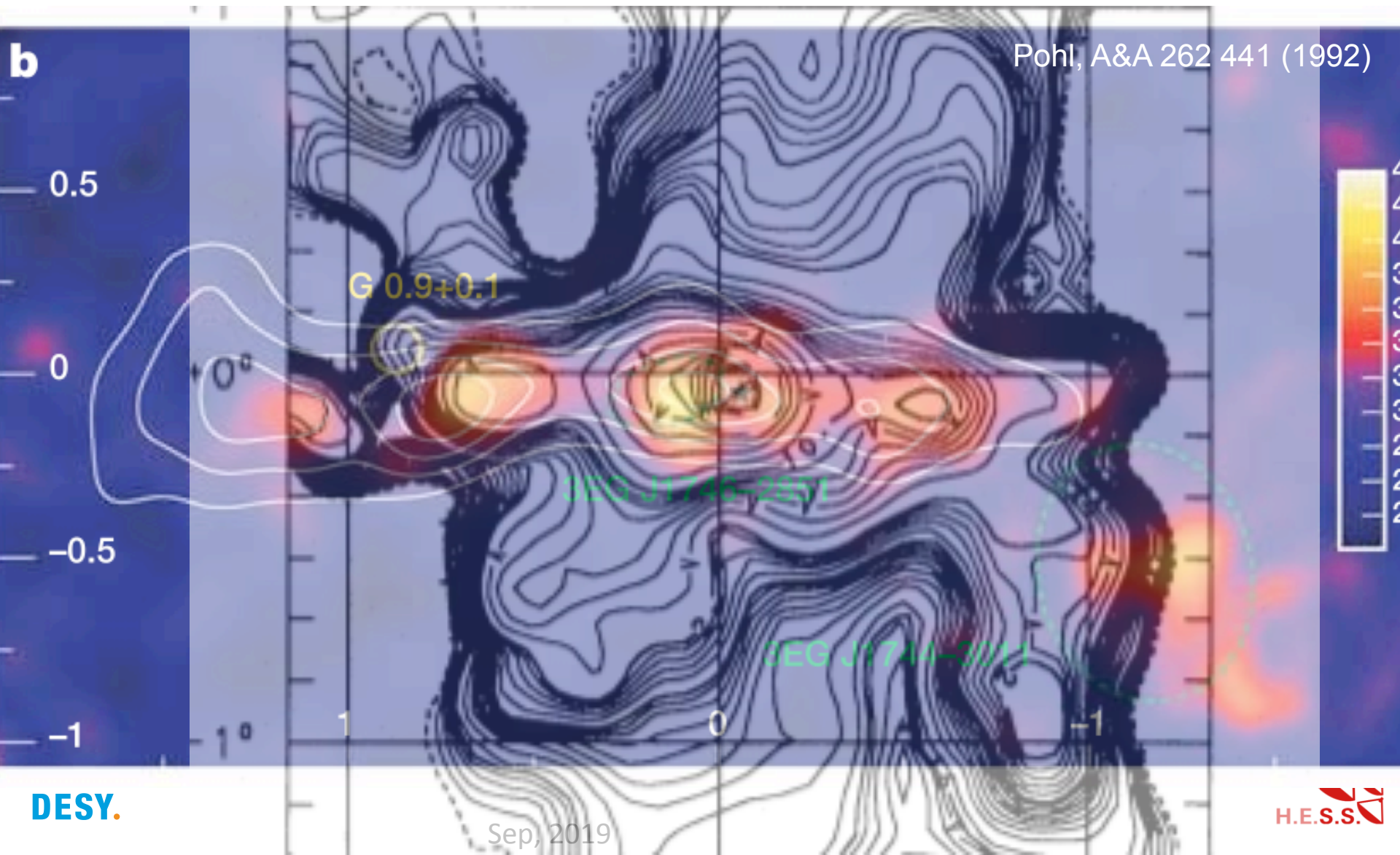
$$\dot{M} \approx 0.1 M_{\odot} \text{ s}_{\text{Sep}}^{-1}, 2019$$

$$L_{\gamma}^{\text{IR}} \approx 10^{42} \text{ erg s}^{-1}$$

Aharonian+, Nature, 439, 695 (2006)



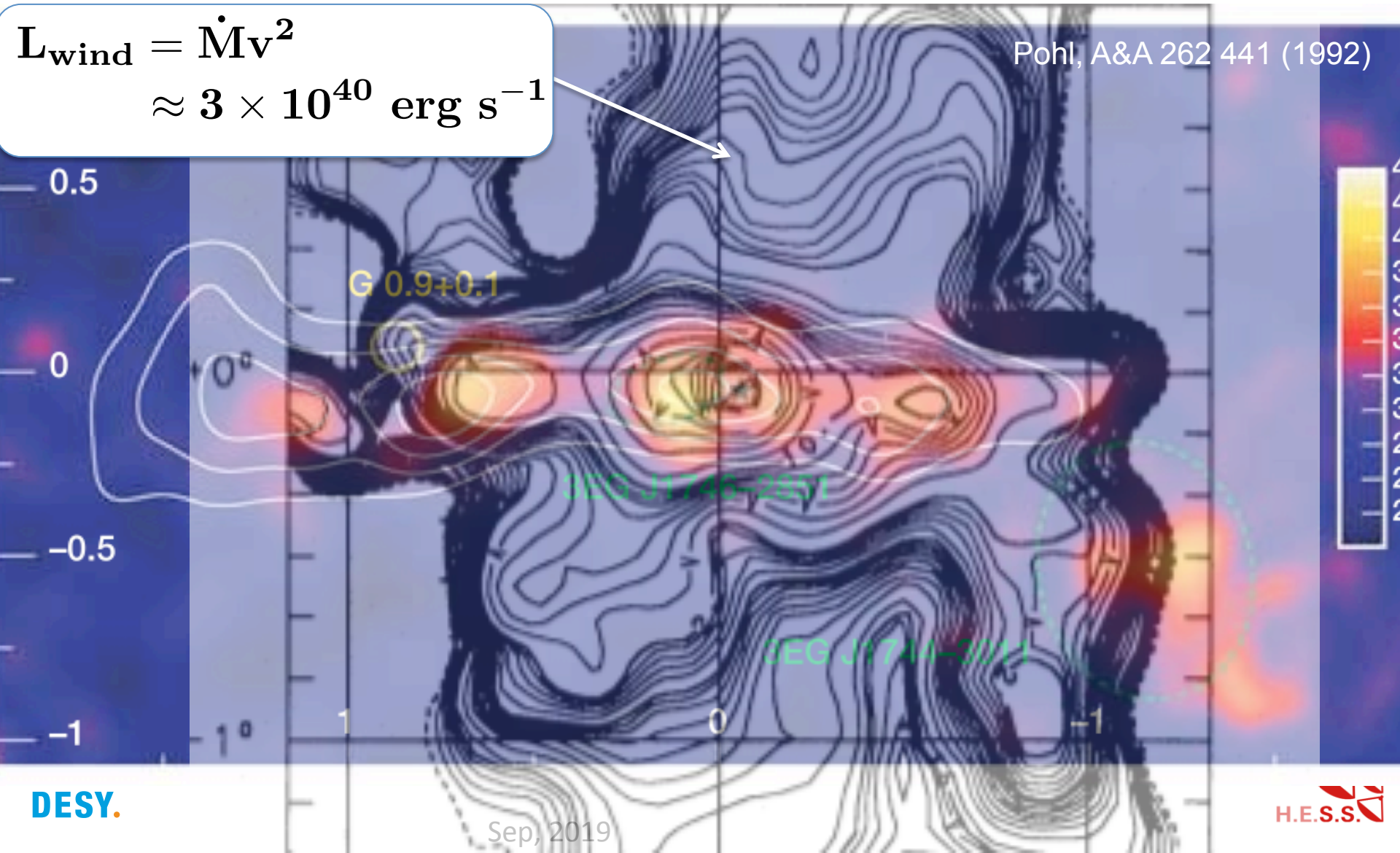
Milky Way- Galactic Center Outflow



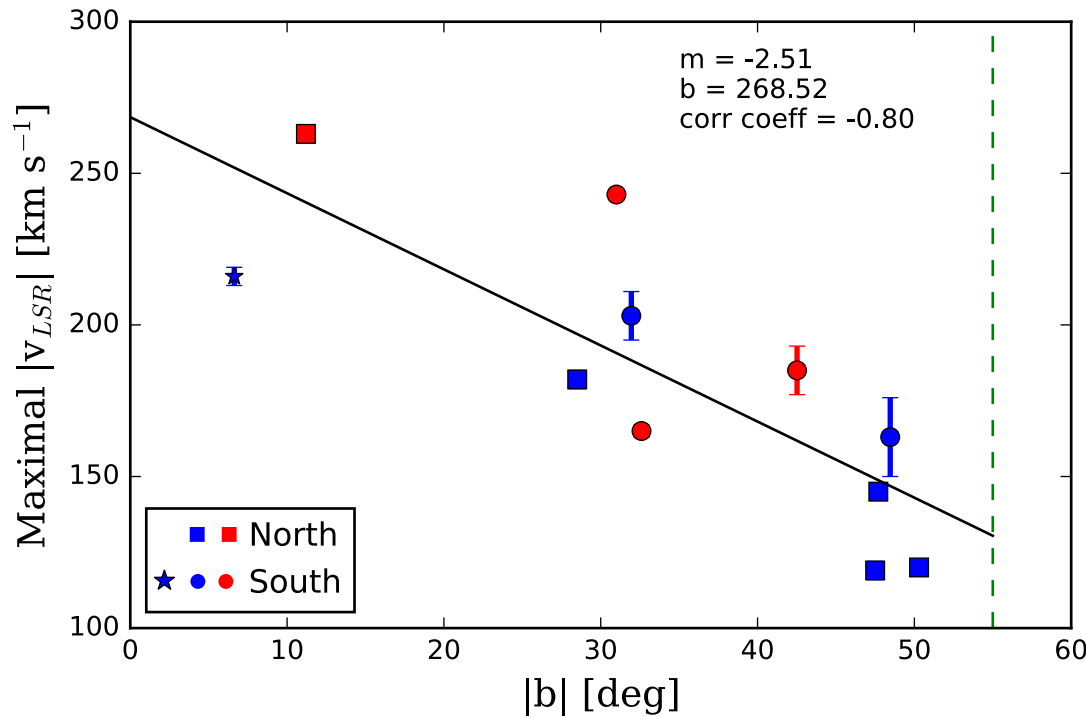
Milky Way- Galactic Center Outflow

$$L_{\text{wind}} = \dot{M} v^2$$
$$\approx 3 \times 10^{40} \text{ erg s}^{-1}$$

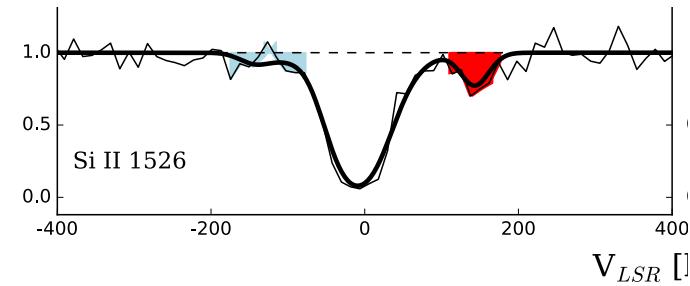
Pohl, A&A 262 441 (1992)



Milky Way- Velocity Profile of Central Chimney



Karim+, Ap.J. 860 (2018)



Nuclear outflow rates:

MW
 $> 0.2 M_{\odot} \text{ yr}^{-1}$

NGC 253:
 $> 3 M_{\odot} \text{ yr}^{-1}$

Bordoloi ApJ 834 191 (2017)

Bolatto+, Nature Letter 12351 (2013)

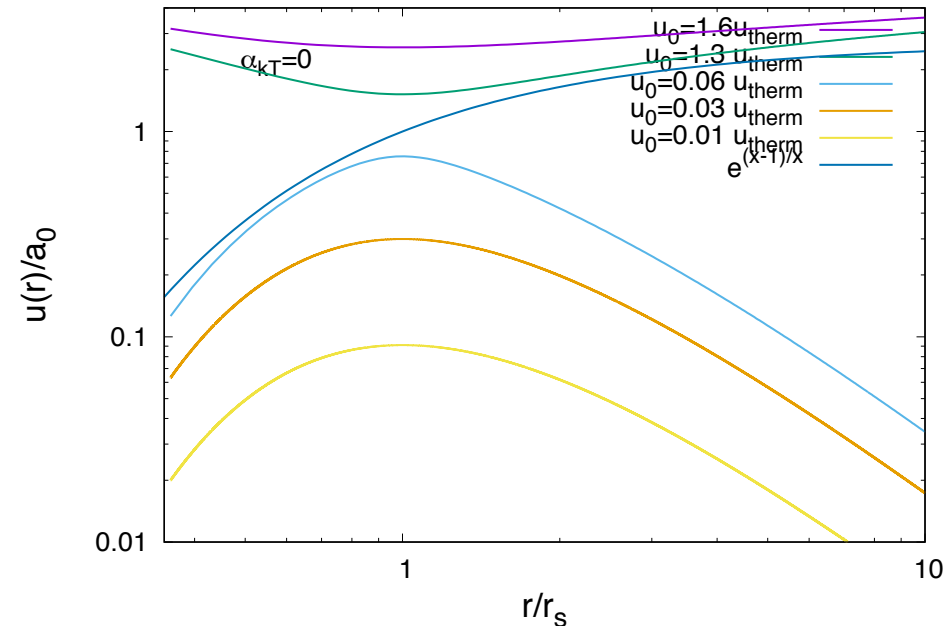
The Fate of Starburst Galaxy Outflows?

$$\rho \mathbf{v} \frac{\partial \mathbf{v}}{\partial r} = -\frac{\partial \mathbf{p}}{\partial r} - \rho \frac{(\mathbf{R}_{\text{Schwarz}}/2)}{r^2}$$

$$\mathbf{p} = \rho kT$$

$$\rho v r^2 = \text{const.}$$

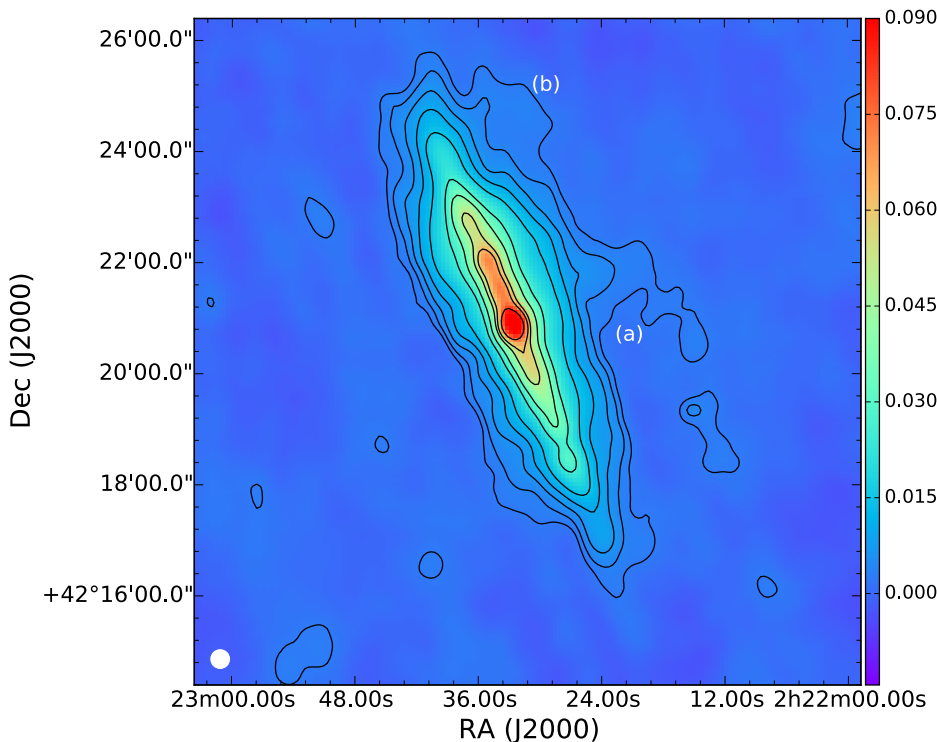
$$\left(1 - \frac{v^2}{kT}\right) \frac{\partial \rho}{\partial r} = -\rho \frac{(\mathbf{R}_{\text{Schwarz.}}/2)}{kT r^2} + \frac{2\rho v^2}{kT r}$$



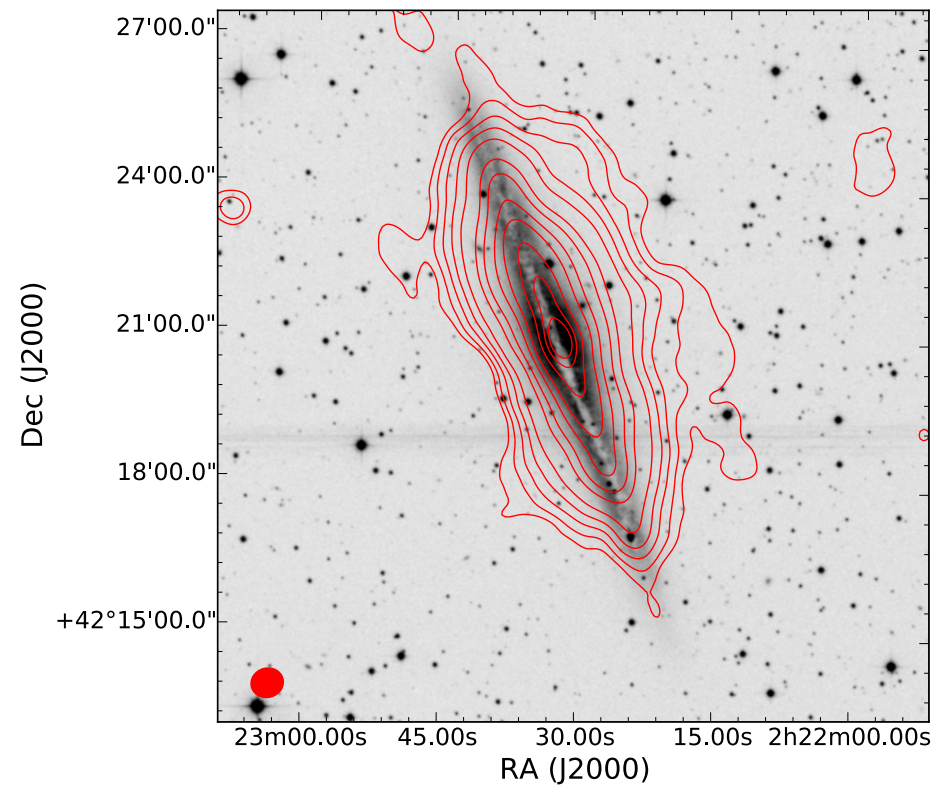
Chamberlain, ApJ 131 (1961)

NGC 891: Radio Perspective (radio halos)

Radio Contour Map- rather good spatial information



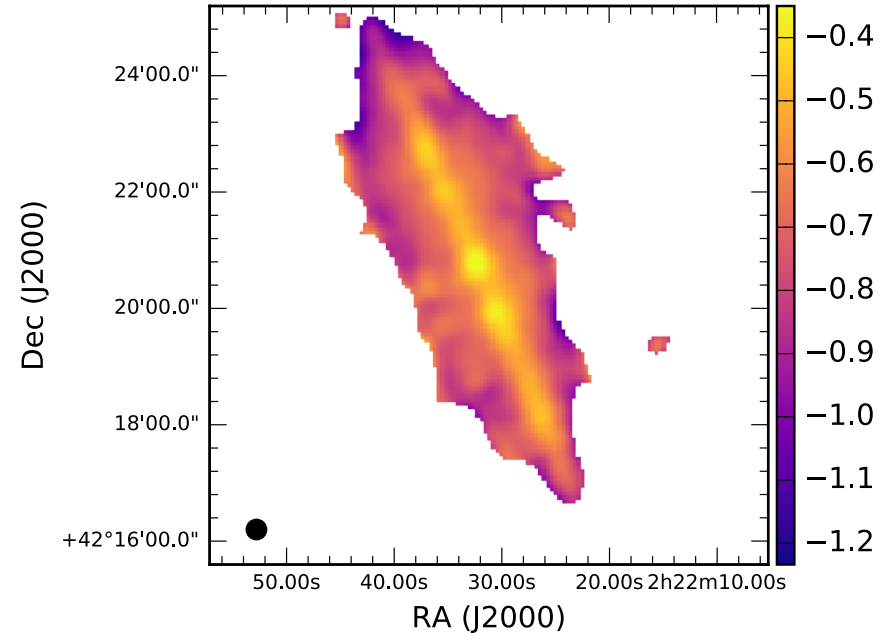
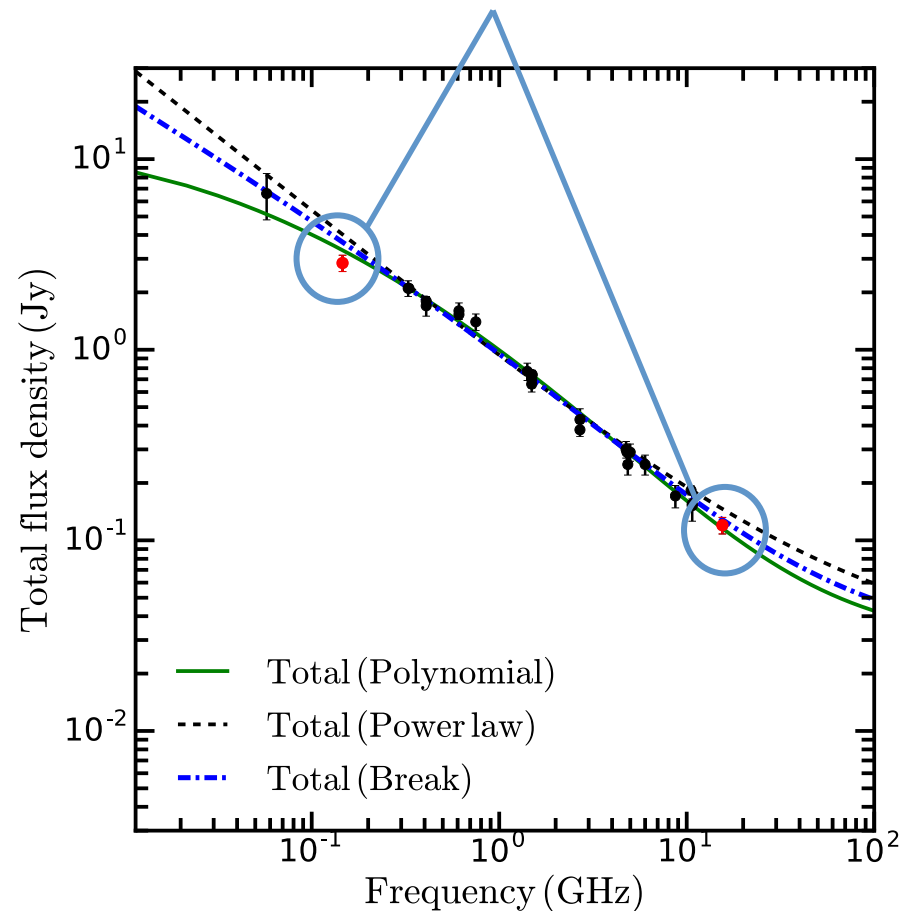
Radio Contours Overlaid onto Optical Image



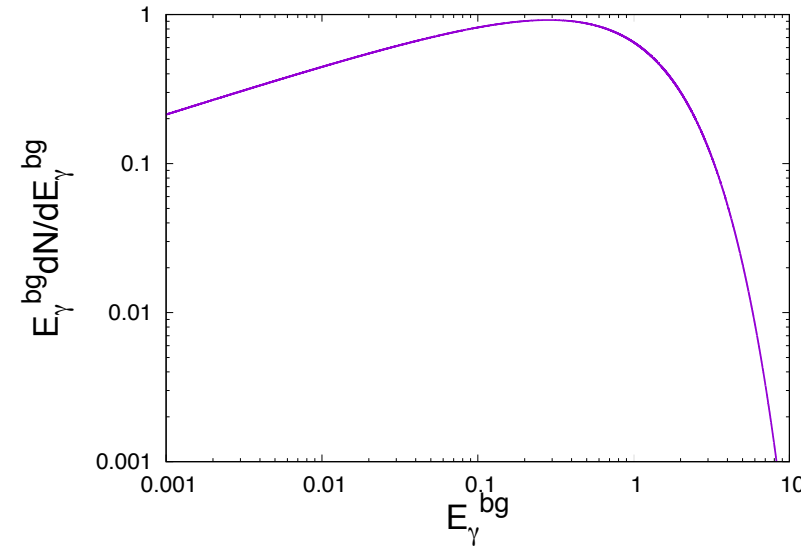
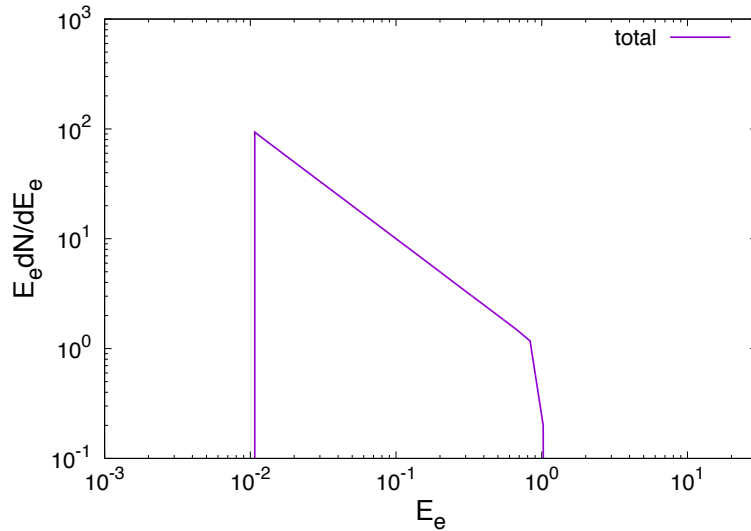
Mulcahy+ 2018, A&A, 891

NGC 891: Radio Perspective (radio halos)

Radio Spectral Coverage- rather poor energy information

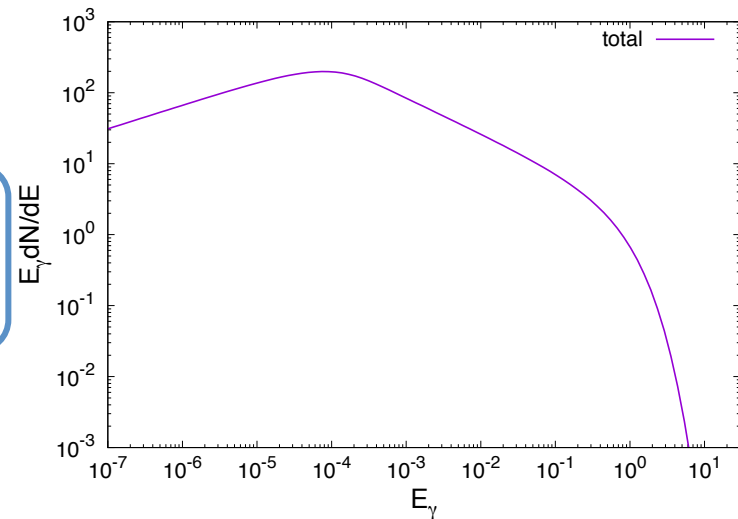


Groundwork- Understanding Synchrotron Emission

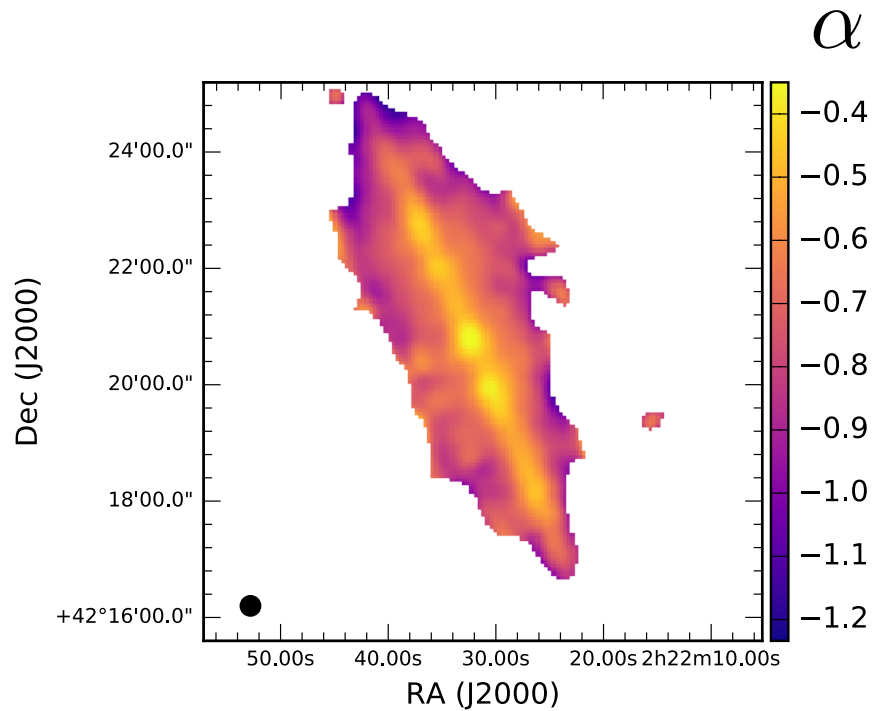


$$E_\gamma = \gamma_e^2 \left(\frac{B}{B_{\text{crit}}} \right) m_e$$

$$E_\gamma \frac{dN}{dE_{\gamma \text{ tot}}} = \int \left(\frac{E_\gamma}{\Gamma_e^2} \right) \frac{dN}{dE_\gamma} \left(\frac{E_\gamma}{\Gamma_e^2} \right) E_e \frac{dN}{dE_e} dE_e$$



NGC 891: Unpicking What's Going On

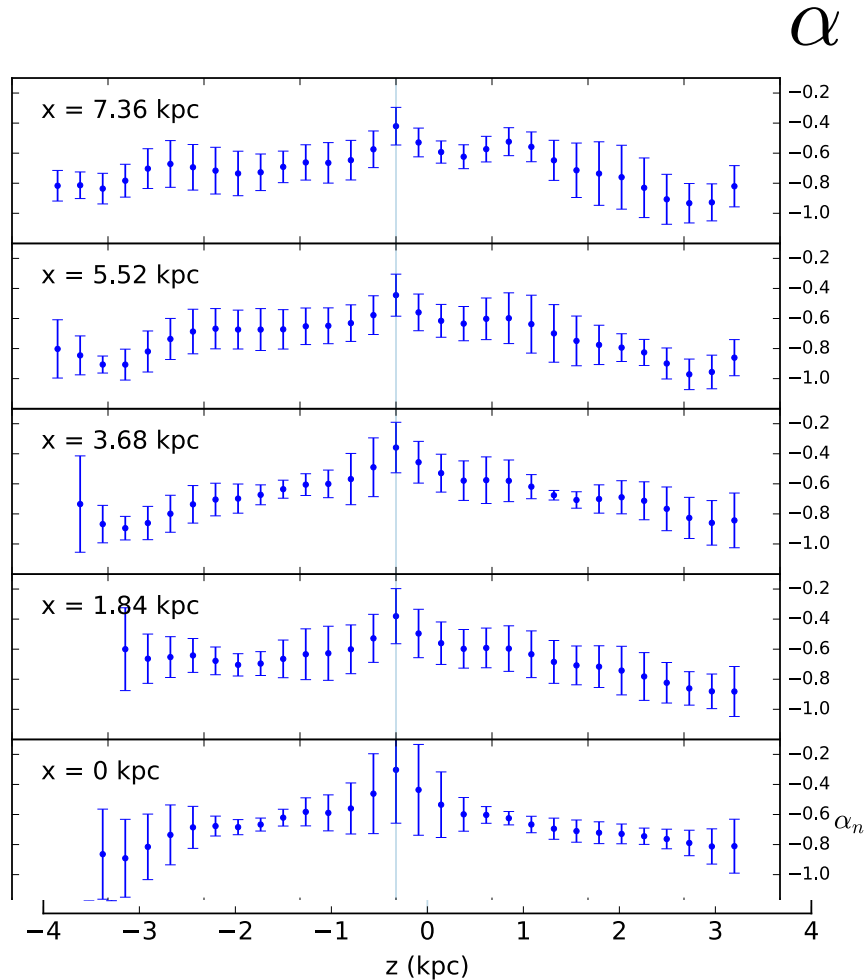


$$E_{\gamma} \frac{dN}{dE_{\gamma}} \propto E_{\gamma}^{\alpha}$$

$$E_e \frac{dN}{dE_e} \propto E_e^{-s}$$

$$\alpha = -s/2$$

NGC 891: Unpicking What's Going On



$$E_\gamma \frac{dN}{dE_\gamma} \propto E_\gamma^\alpha$$

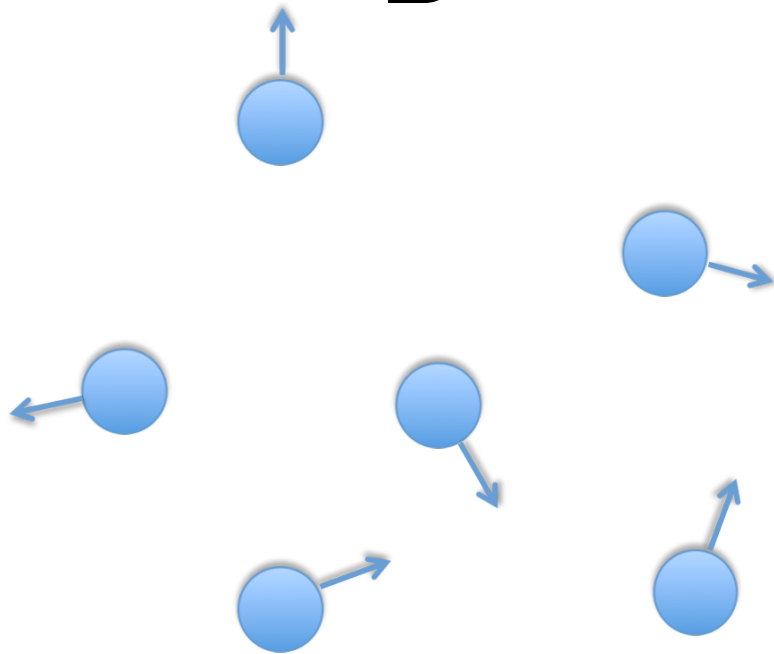
← Spectral index gets softer (ie. larger) with distance from the Galactic plane

How do electrons get transported out into the halo? Do they diffuse or advect?

How Do Non-Thermal Particles Get Transported Out of their Host Galaxy?

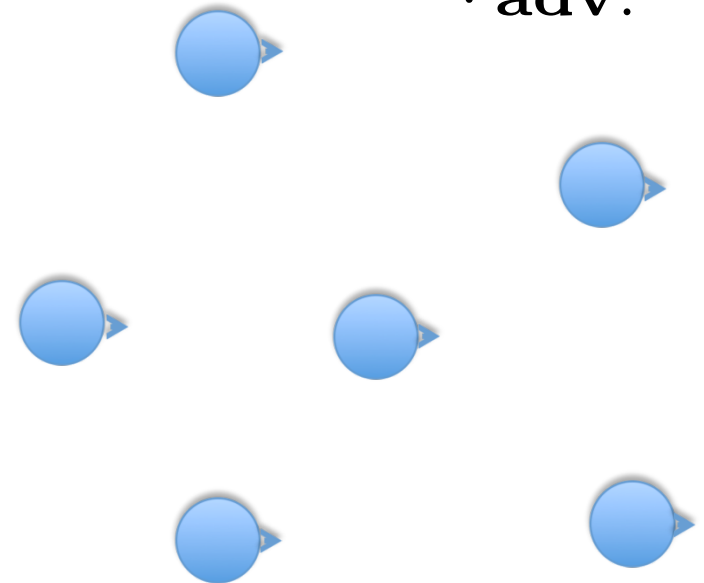
Diffusive Escape

$$t_{\text{diff.}} = \frac{R^2}{D}$$



Advective Escape

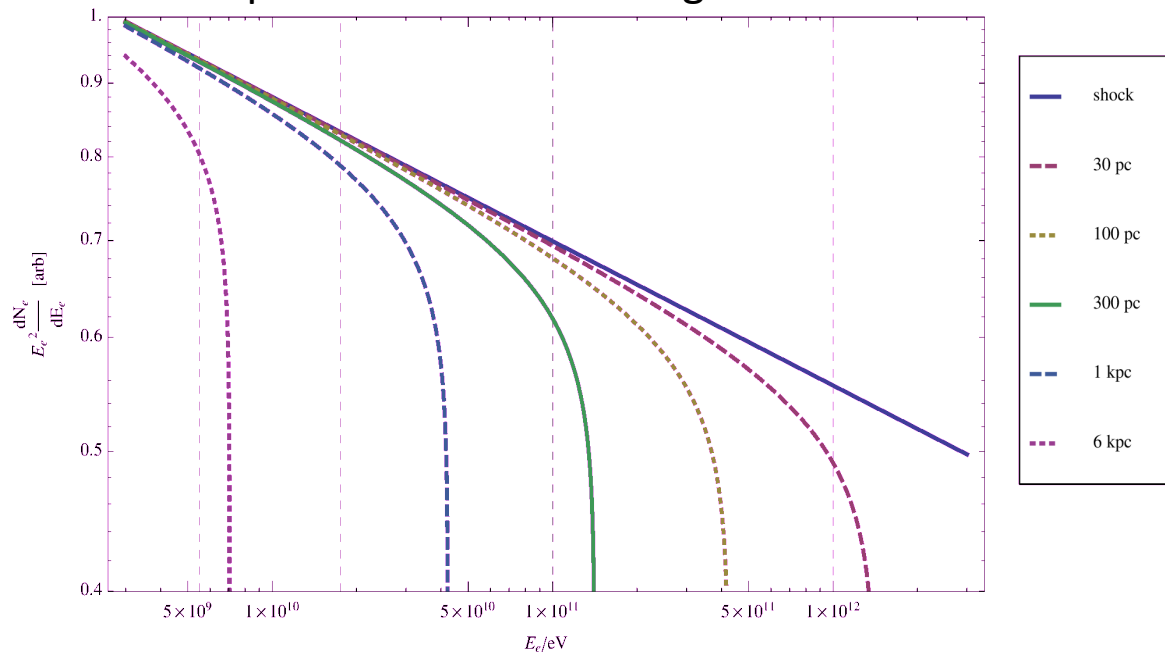
$$t_{\text{adv.}} = \frac{R}{v_{\text{adv.}}}$$



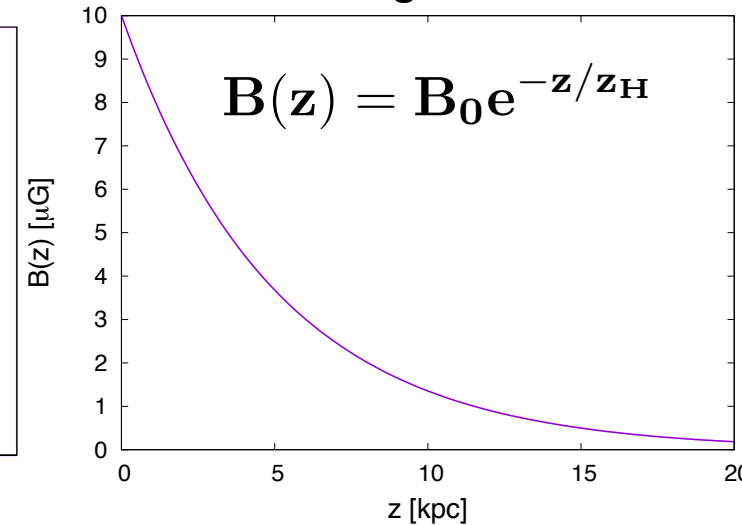
Electron Spectra within an Advective Outflow

$$\tau_e \approx 60 \left(\frac{5 \text{ GeV}}{E_e} \right) \left(\frac{6 \mu\text{G}}{B} \right)^2 \text{ Myr}$$

Electron Spectra at Different Heights Above Disk



B-field Strength Profile



Crocker+, Ap.J. 808 (2015)

Electron Spectra within an Advective Outflow

Advective Transport

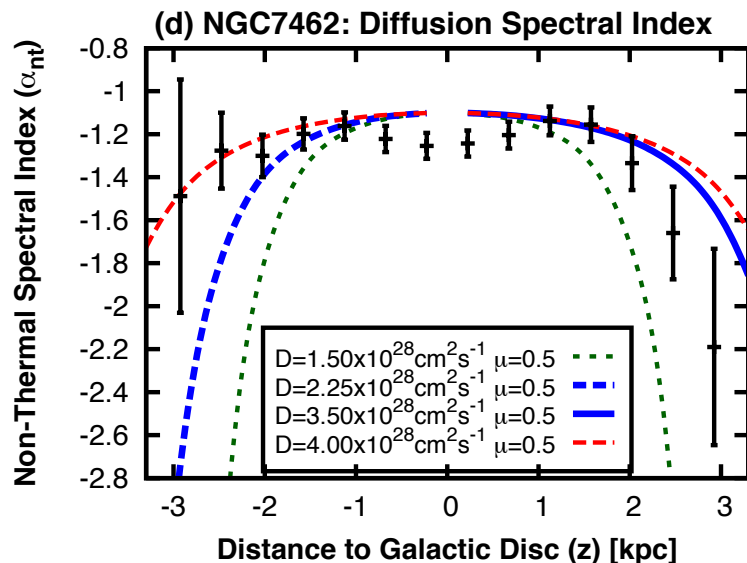
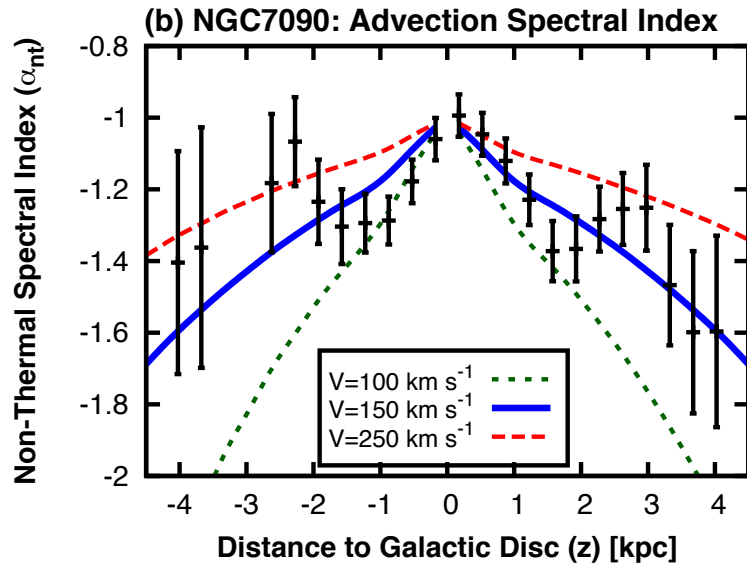
$$t_{\text{adv.}} = \frac{R}{V_{\text{adv.}}}$$

Diffusive Transport

$$t_{\text{diff.}} = \frac{R^2}{D}$$

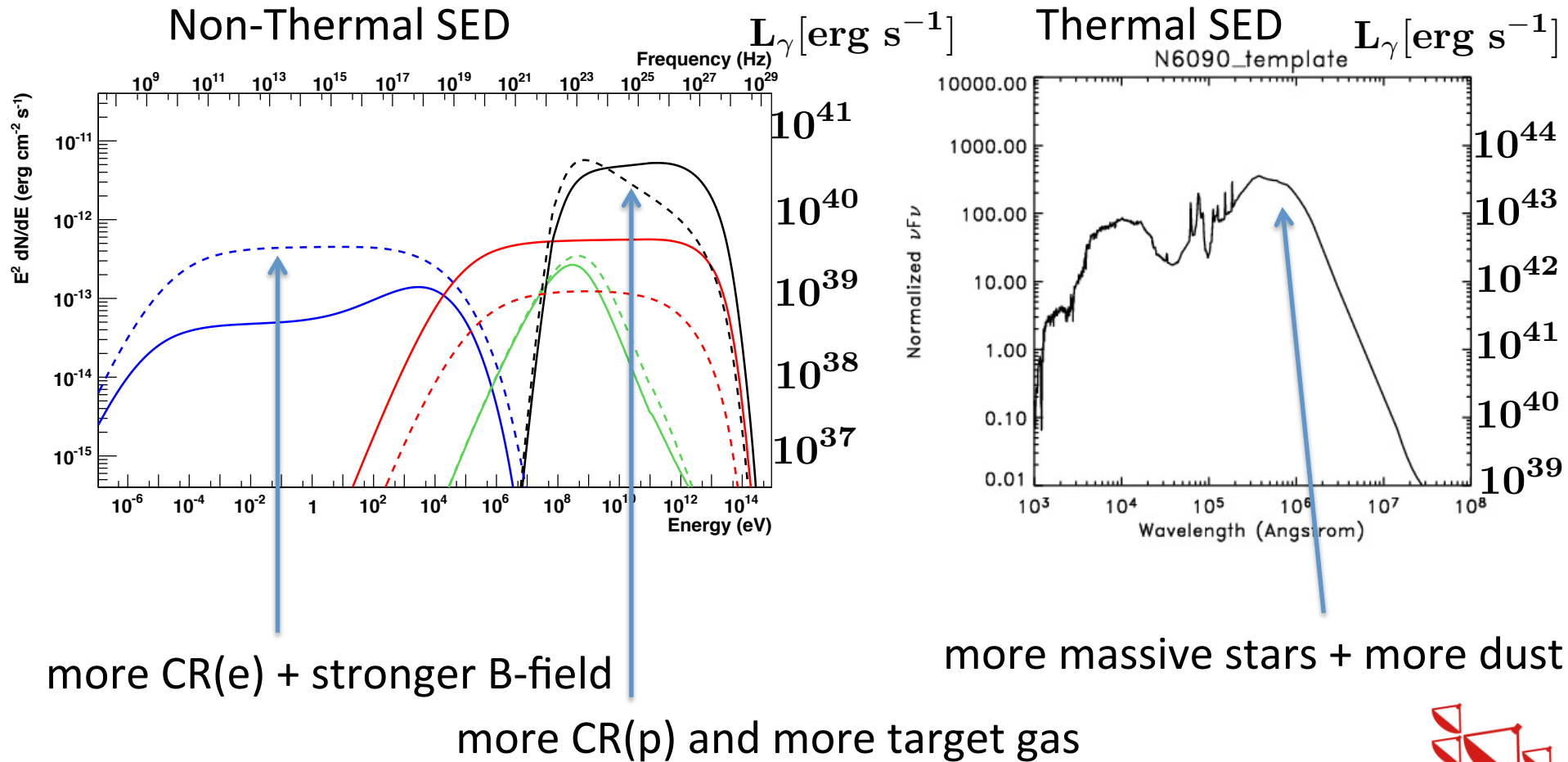
Heesen+ MNRAS, 458, 1 (2016)

Heesen+ A&A 494, 563–577 (2009)



An Understanding of NGC 253 Global SED

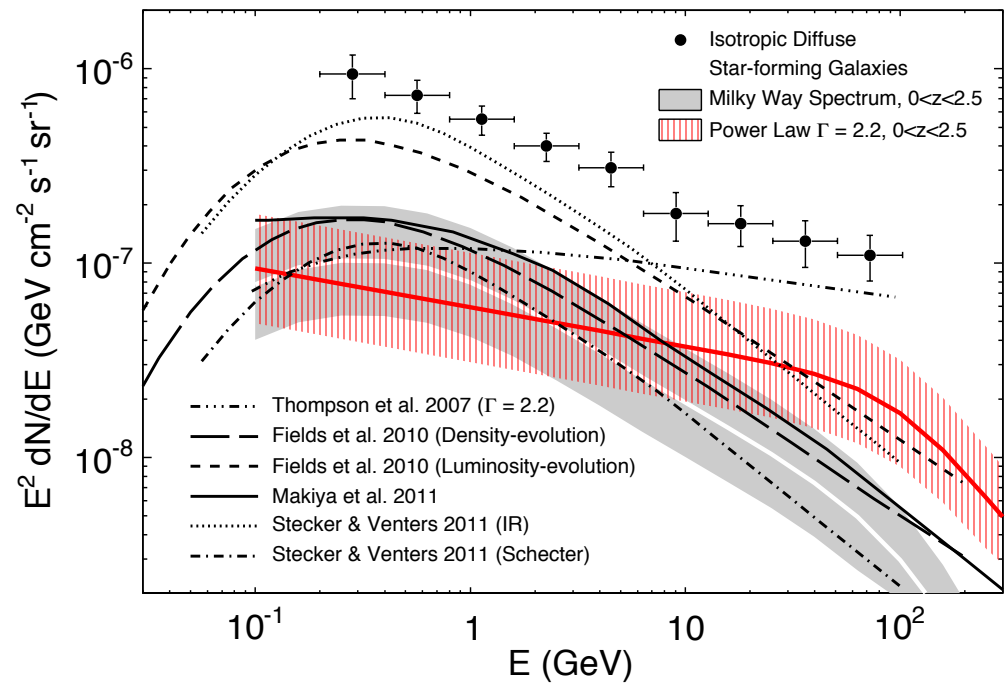
Ohm+, IAU Symp. No. 284 (2012)



Contribution of Starburst Galaxies to Isotropic Gamma-Ray Background

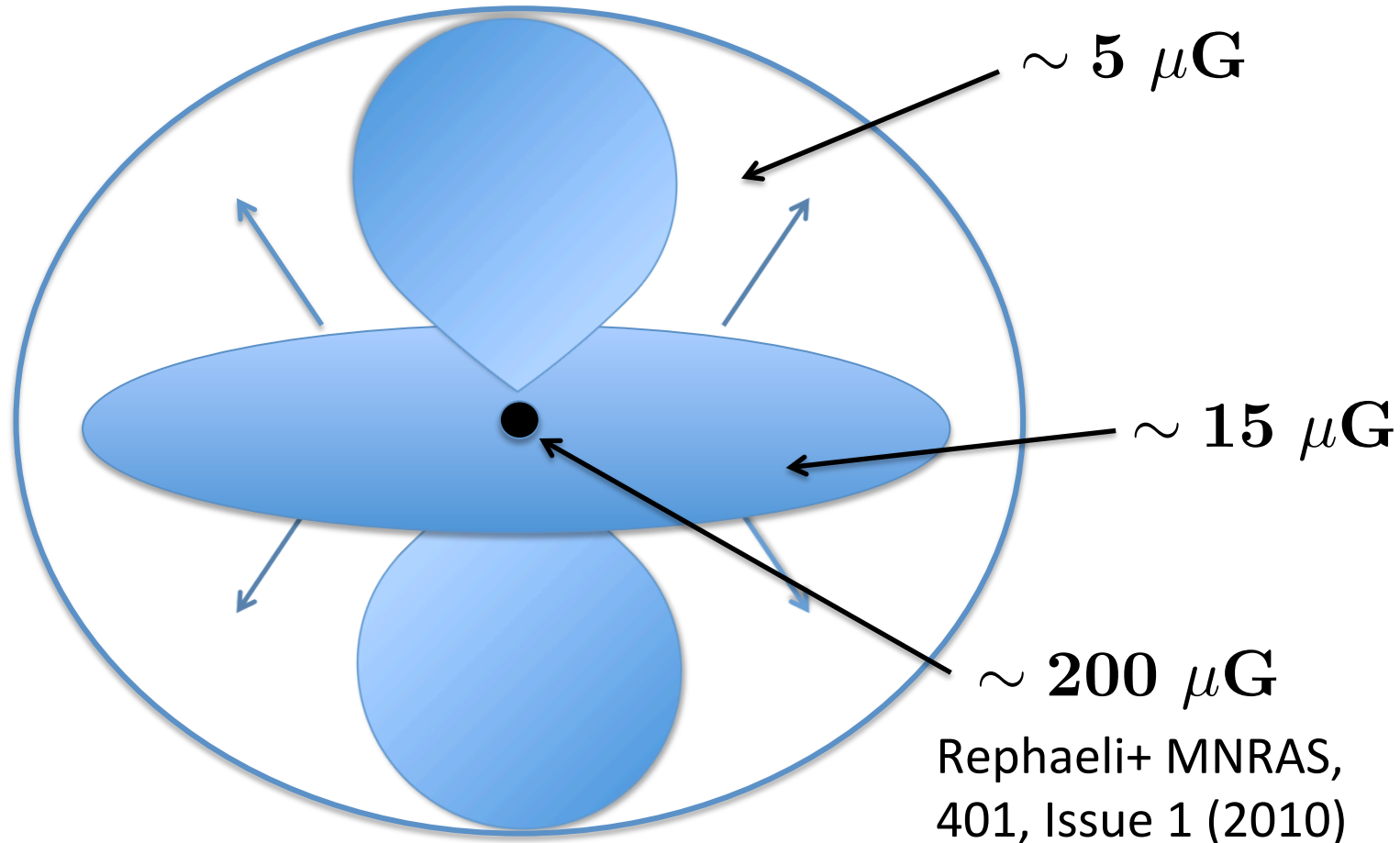
Estimated contribution to the diffuse gamma-ray background from starburst galaxies

$$\mathbf{I} = \frac{\mathbf{c}}{4\pi} \int_0^\infty \rho_{\mathbf{L}}(\mathbf{z}) \frac{1}{(1 + \mathbf{z})^2 \mathbf{H}(\mathbf{z})} d\mathbf{z}$$

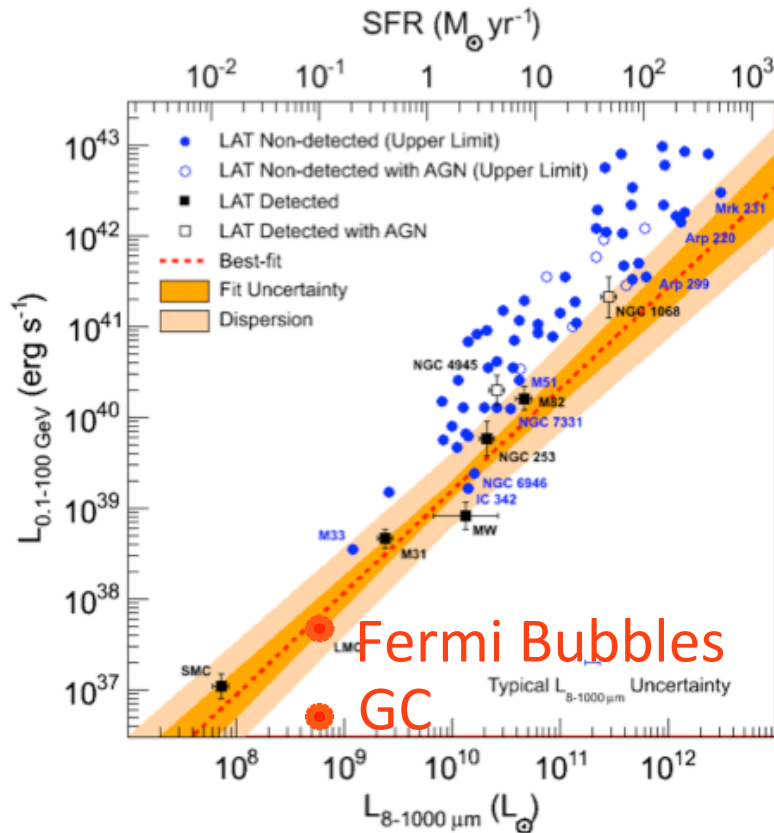


Magnetic Fields Throughout Starburst Galaxies?

Elstner+ A&A 568, A104 (2014)



Gamma-Ray-Infrared Correlation



Ackermann+, ApJ, 755 (2012)

Particle Acceleration in Starburst Systems

$$t_{\text{acc}} = \eta \frac{R_{\text{lar}}}{c\beta^2}$$

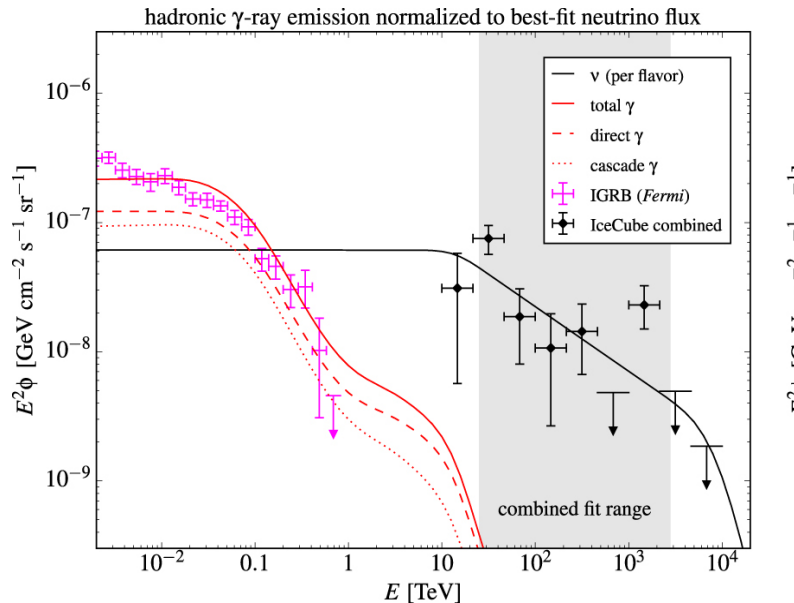
$$t_{\text{diff.}} = \frac{R^2}{\eta c R_{\text{lar}}}$$

Maximum energy
(Hillas criterion)

$$R_{\text{lar}} = \frac{\beta}{\eta} R$$

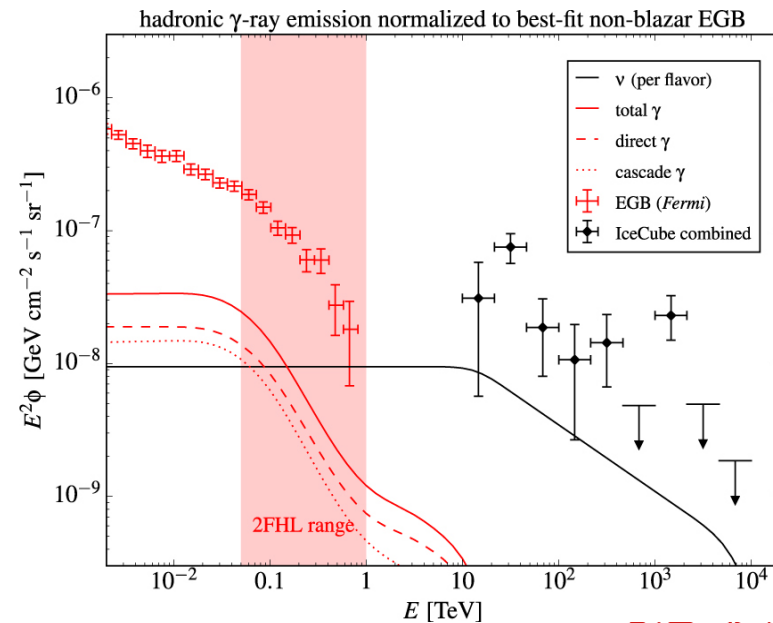
$$R_{\text{lar}}(E, B) = \left(\frac{E}{1 \text{ PeV}} \right) \left(\frac{100 \mu\text{G}}{B} \right) 0.01 \text{ pc}$$

Starburst Galaxies: Neutrinos



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

K. Bechtol + 2017
ApJ, 836



Power Sources of Galactic Outflows

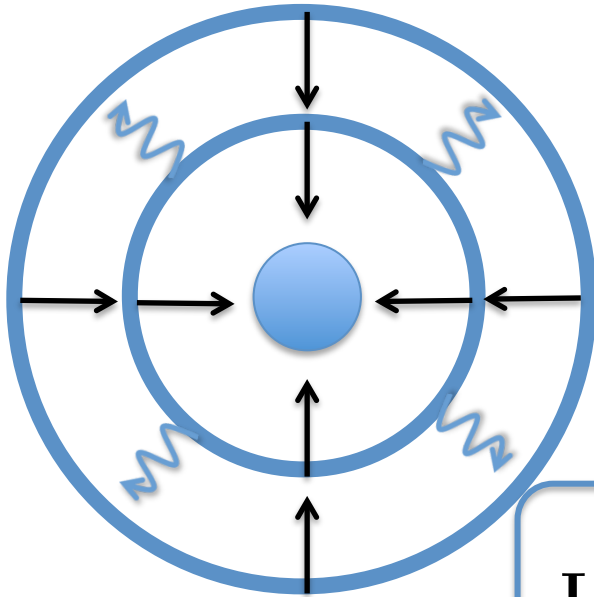
Outflow KE flux, CR, magnetic fields all being driven out of the Galaxy....but by what?

Stellar Wind/Supernova KE Driven

AGN Outflow KE Driven

Cosmic Ray Driven

Radiation Pressure Driven Winds

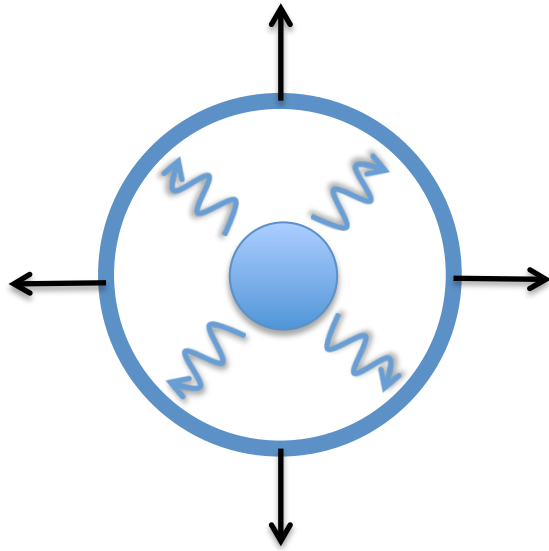


$$dE = \frac{GM(Nm_p)}{R^2} dR$$

$$f = \frac{N\sigma_T}{4\pi R^2}$$

$$L_{\text{Edd.}} = \frac{4\pi f G M m_p c}{\sigma_T} \approx 10^{38} \left(\frac{M}{M_\odot} \right) \text{ erg s}^{-1}$$

Reminder- Eddington Limit



$$L_{\text{Edd.}} = \frac{4\pi f G M m_p c}{\sigma_T} \approx 10^{38} \left(\frac{M}{M_{\odot}} \right) \text{ erg s}^{-1}$$

$$\frac{L}{L_{\odot}} \approx \left(\frac{M}{M_{\odot}} \right)^{3.5}$$

Eg. Luminosity of Eta Carina (a massive stellar binary) is:

$$L_{\gamma}^{\text{th.}} \approx 10^{39} \text{ erg s}^{-1}$$

$$L_{\text{wind}} \approx 3 \times 10^{37} \text{ erg s}^{-1}$$

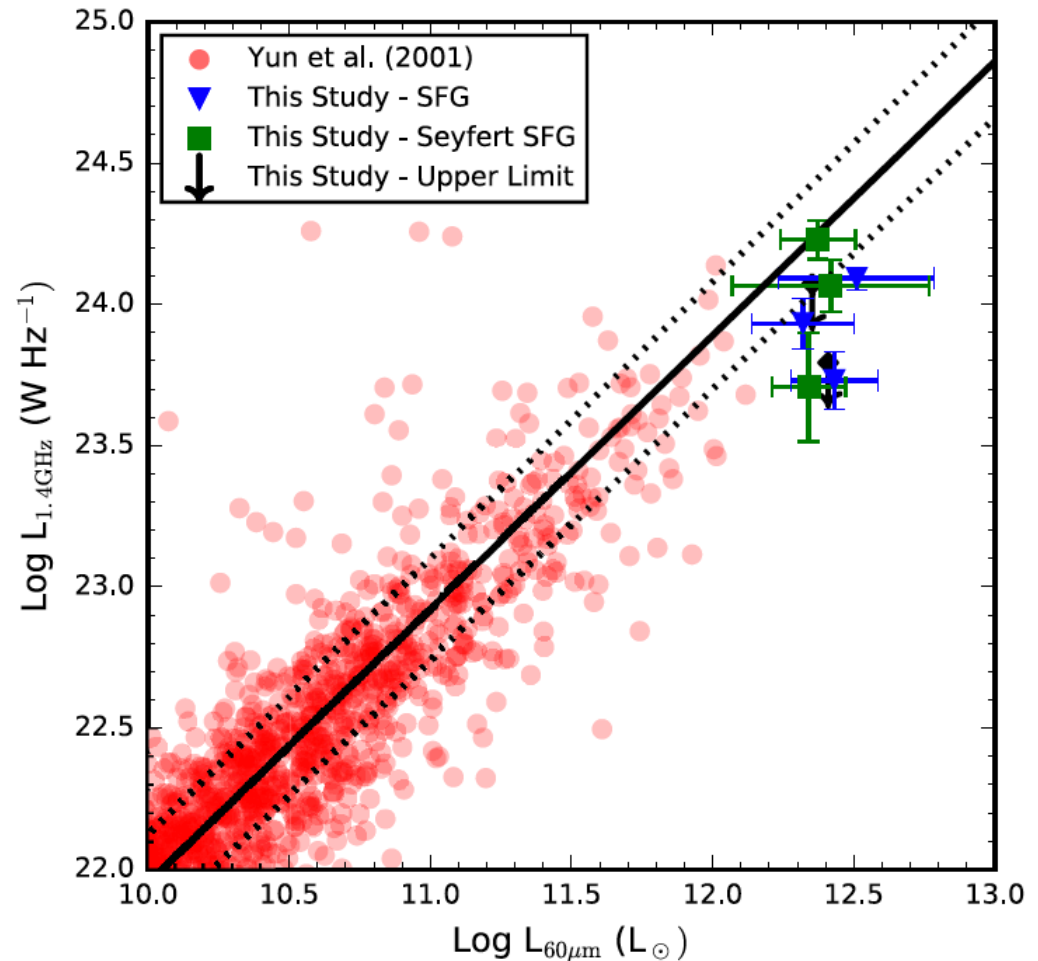
Power Sources of Galactic Outflows

Stellar Wind/Supernova KE Driven
(Veilleux 2005)

- OB stars winds dominate < 3 Myr
- WR stars winds dominate 3-6 Myr
- Core Collapse Type II SN dominate until 40 Myr

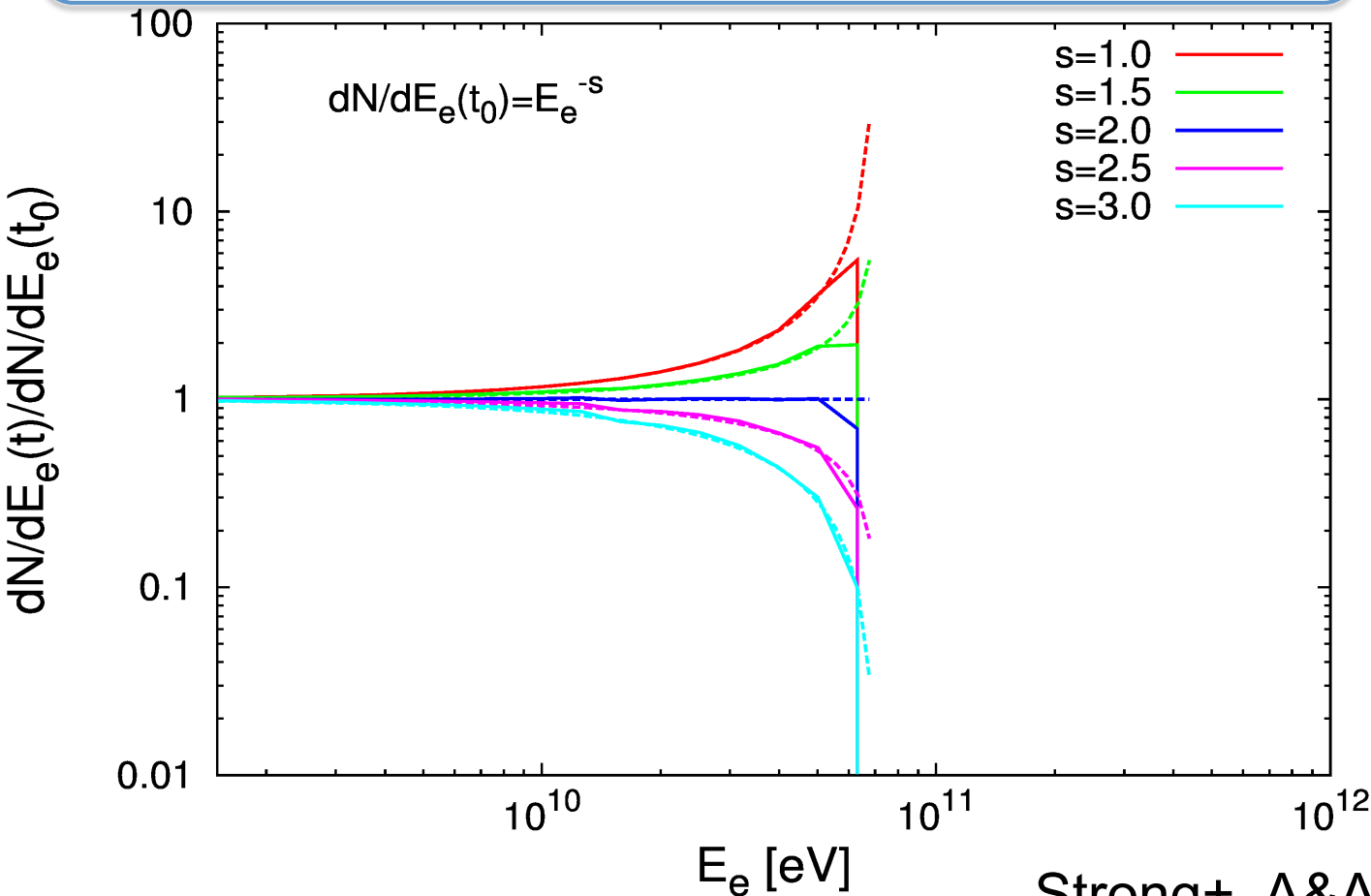
III. Statistical Ensembles of Galaxies

Starburst Galaxies: Relation Between Non-Thermal + Thermal Emission



Electron Spectra and Cooling

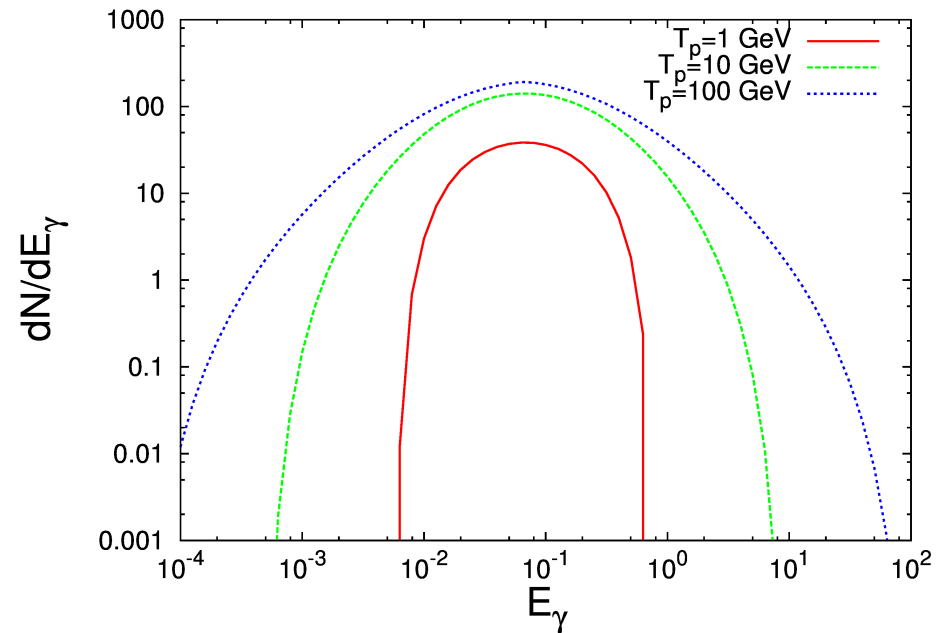
$$E^2 \frac{dN}{dE}(t) = E^2 \frac{dN}{dE}(t_0) \left(1 - \frac{t}{\tau(E)}\right)^{s-2}$$



Strong+, A&A 66 (1978)

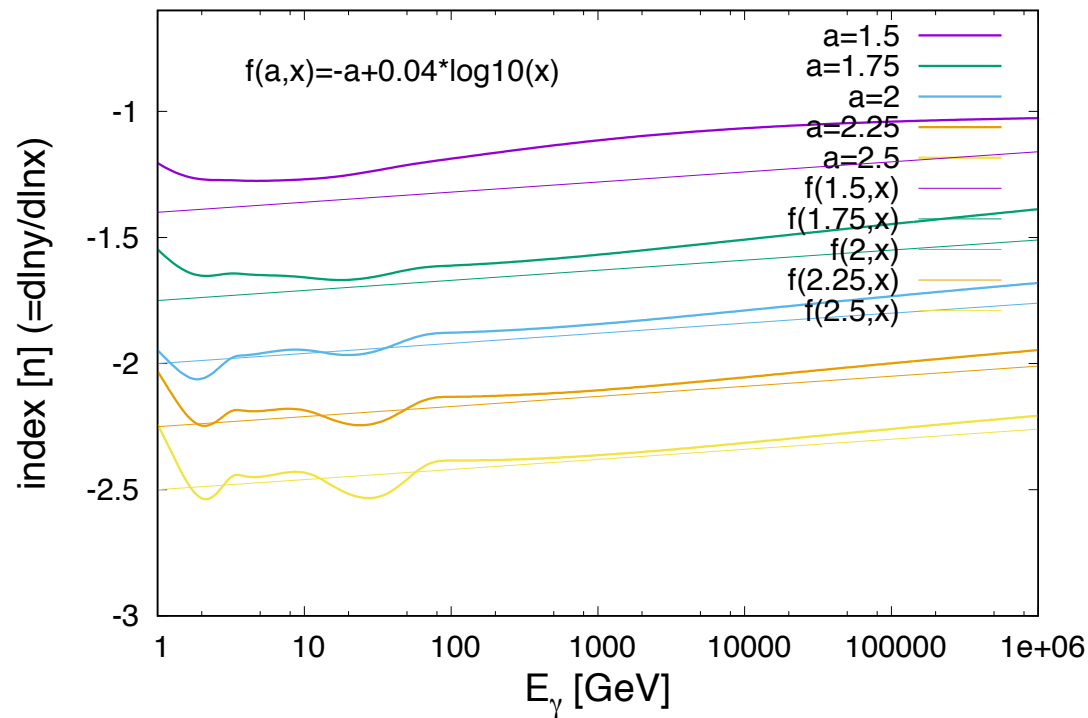
NGC 253: Hadronic Gamma-Ray Emission

$$\frac{d\sigma}{dE_\gamma}(T_p, E_\gamma) = A_{\text{max}}(T_p) \times F(T_p, E_\gamma)$$



NGC 253: Hadronic Gamma-Ray Emission

$$\Phi_{\gamma}(E_{\gamma}) = 4\pi n_{\text{H}} \int \frac{d\sigma}{dE_{\gamma}}(p_p, E_{\gamma}) J(p_p) dp_p$$



$$J_p(p_p) = \frac{A}{p_p^{\alpha}} \exp \left[- \left(\frac{p_p}{p_p^{\max}} \right)^{\beta} \right]$$

Note- the decrease of the index per decade varies between hadronic models (eg. Pythia8, SIBYLL, QGSJET).

NGC 253: Gamma-Ray Perspective

- Energy Loss Timescales

$$t_{pp} = \left(\frac{1}{n_p \sigma_{pp} K_{pp}} \right)$$

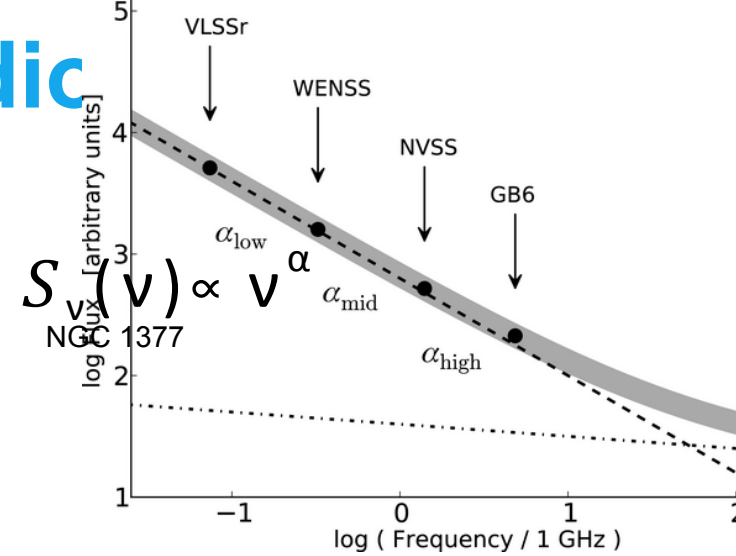
$$t_e(E_e) = \frac{m_e^2}{(4/3) E_e \sigma_T U_{\gamma/B}}$$

$$t_{pp} \approx 10^5 \left(\frac{500 \text{ cm}^{-3}}{n_p} \right) \text{ yrs}$$

$$t_e = 10^5 \left(\frac{5 \text{ GeV}}{E_e} \right) \left(\frac{500 \text{ eV cm}^{-3}}{U_{\gamma/B}} \right) \text{ yrs}$$

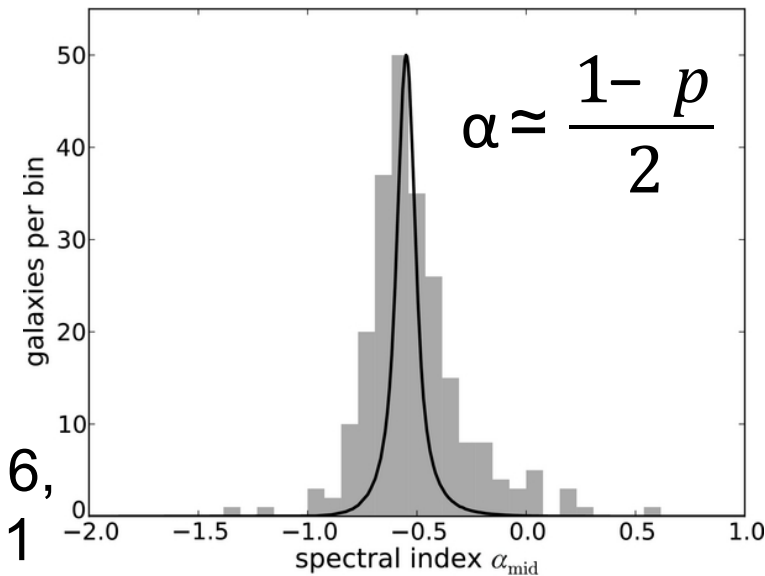
Starburst Galaxies: Radio

- 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 IR

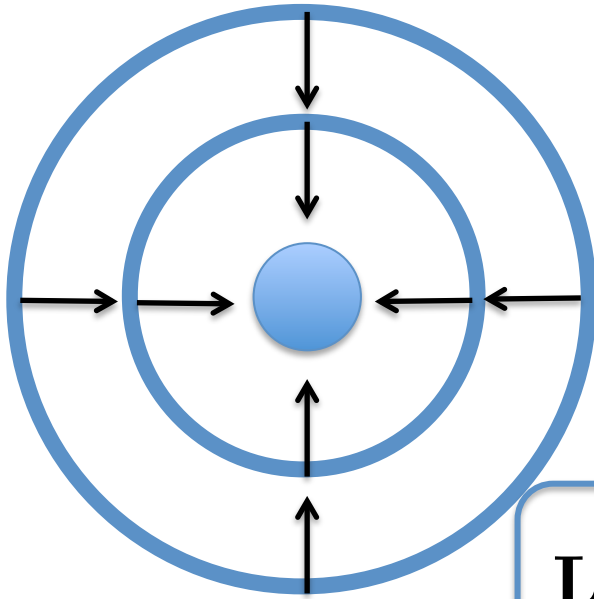


Marvil + 2015
AJ, 149, 32

Galvin+ 2016,
MNRAS, 461



Radiation Pressure Driven Winds



$$dE = \frac{GM(Nm_p)}{R^2} dR$$

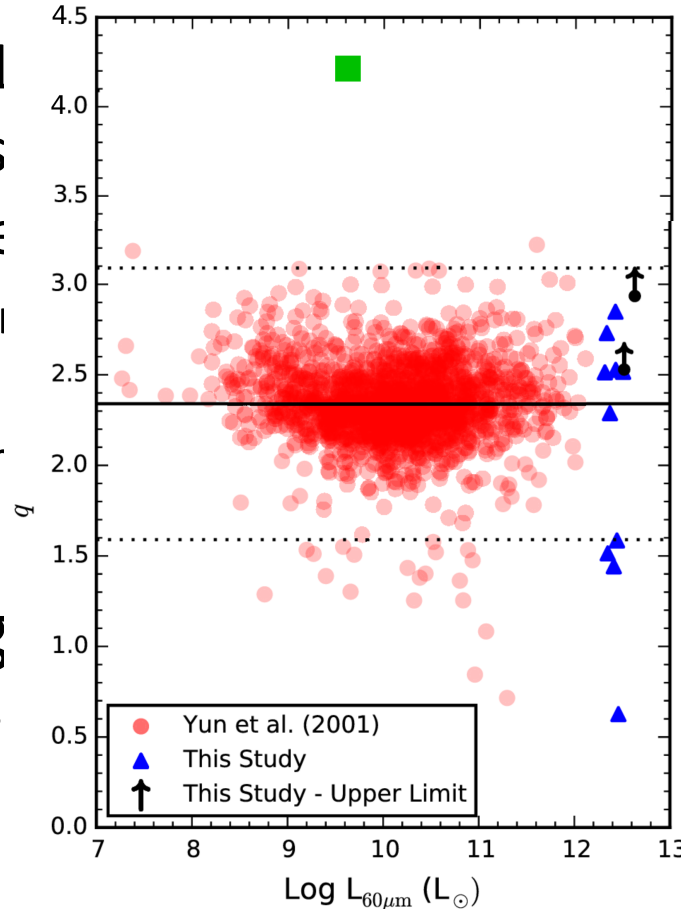
$$f = \frac{N\sigma_T}{4\pi R^2}$$

$$L_{\text{Edd.}} = \frac{4\pi GMm_p c}{\sigma_T}$$

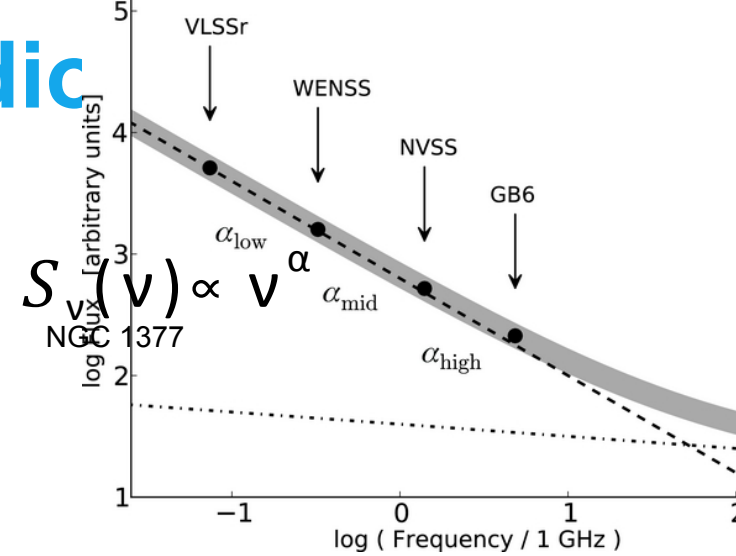
Starburst Galaxies: Radio

- At 1.4 GHz (21 cm) non-thermal emission dominates the spectrum
 - Average spectral index $\alpha \approx -0.7$
 - Average thermal emission $\sim 10\%$
- Higher magnetic field strength
 - $B > 100 \mu\text{G}$

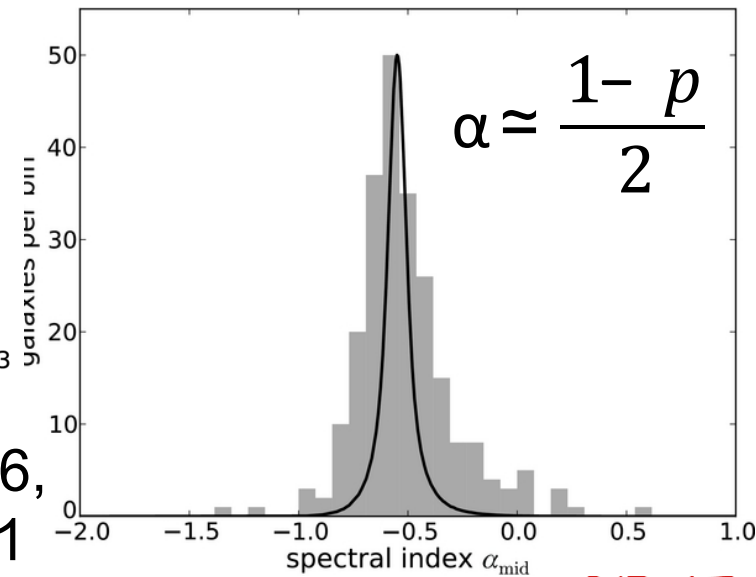
- Correlated with IR



Galvin+ 2016,
MNRAS, 461



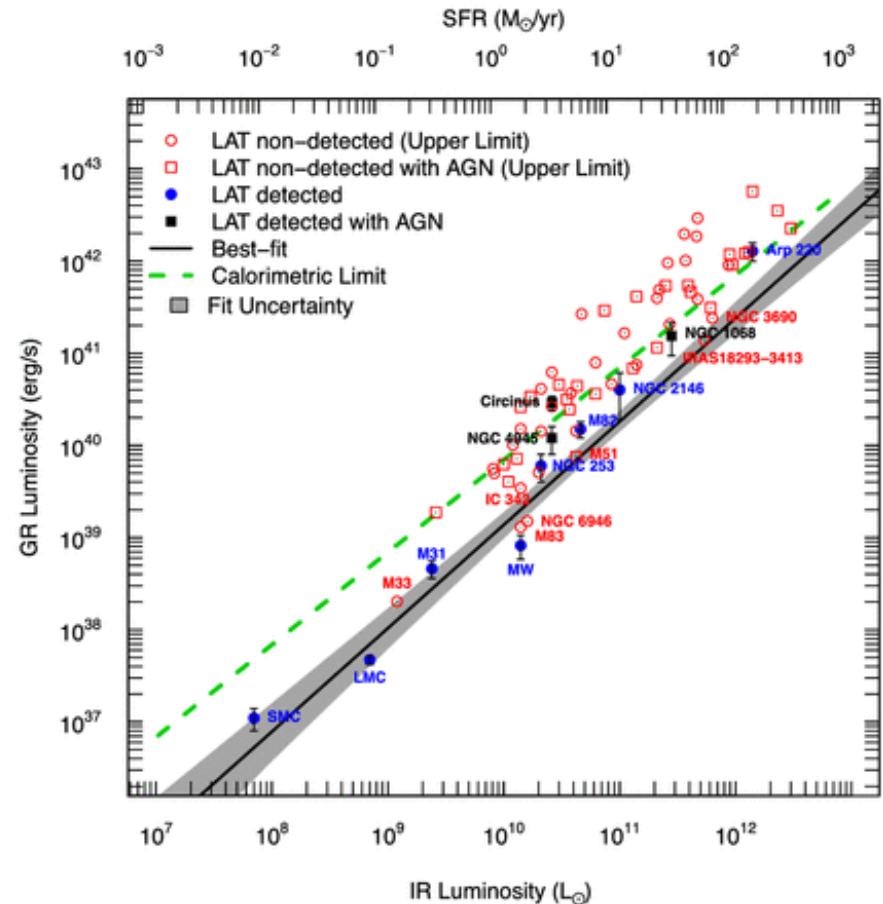
Marvil + 2015
AJ, 149, 32



Starburst Galaxies: Gamma-Ray Perspective

- 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

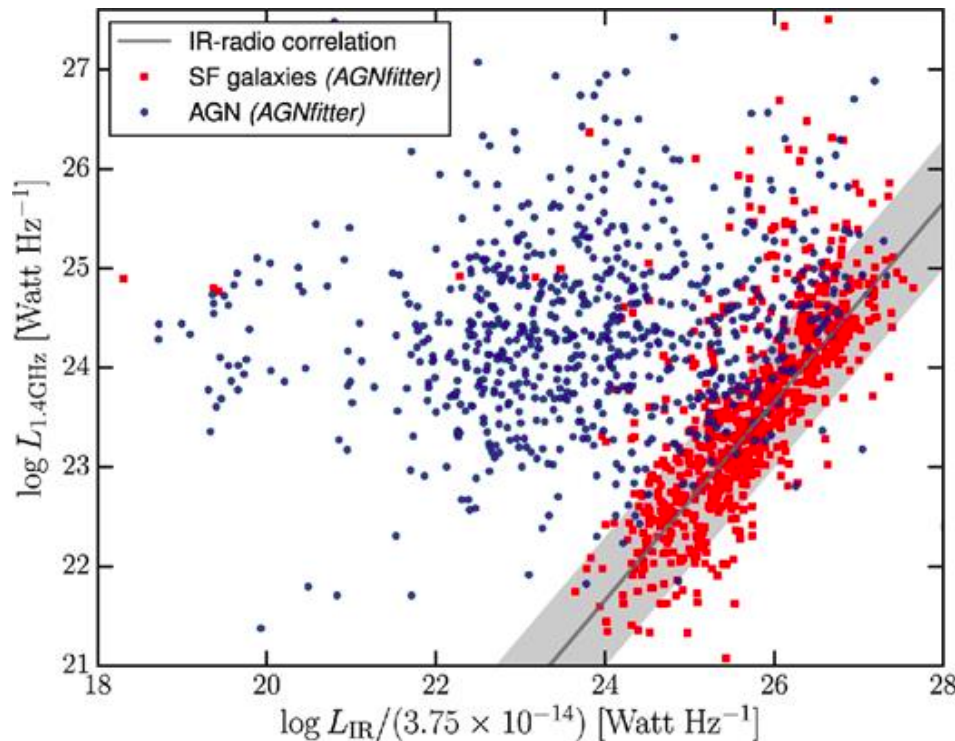


Rojas-Bravo & Araya 2016,
MNRAS, 463

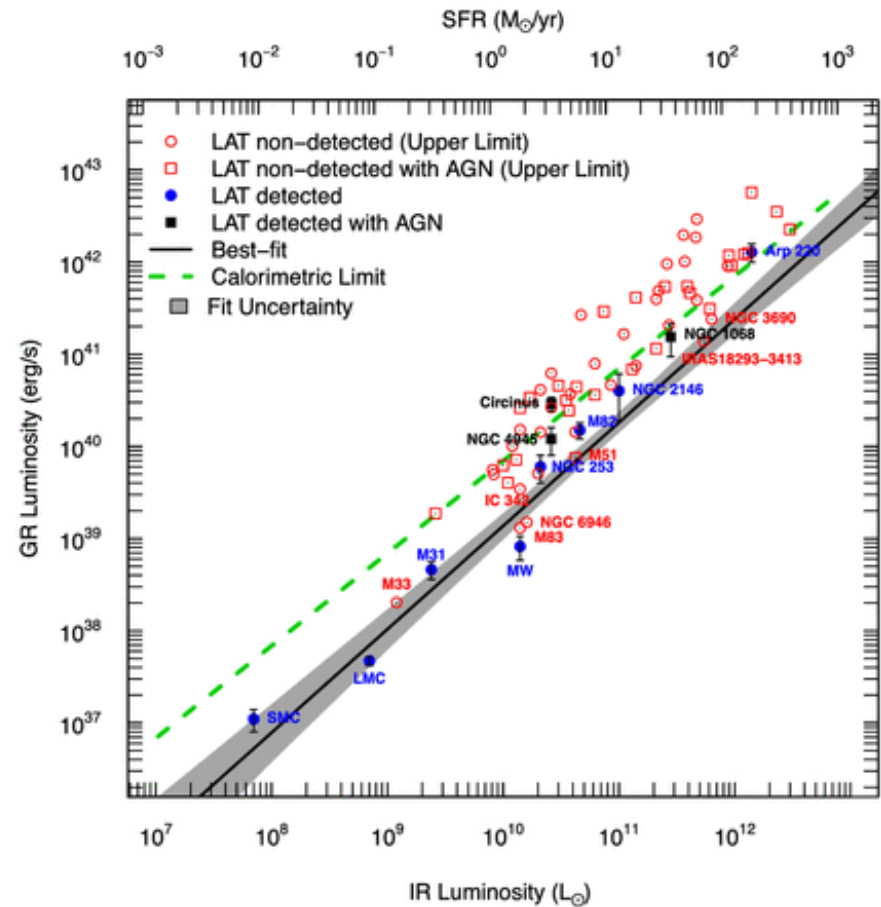
Energies in Starburst Galaxies

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

Far-Infrared Connection



Calistro Rivera+ 2017
MNRAS, 469



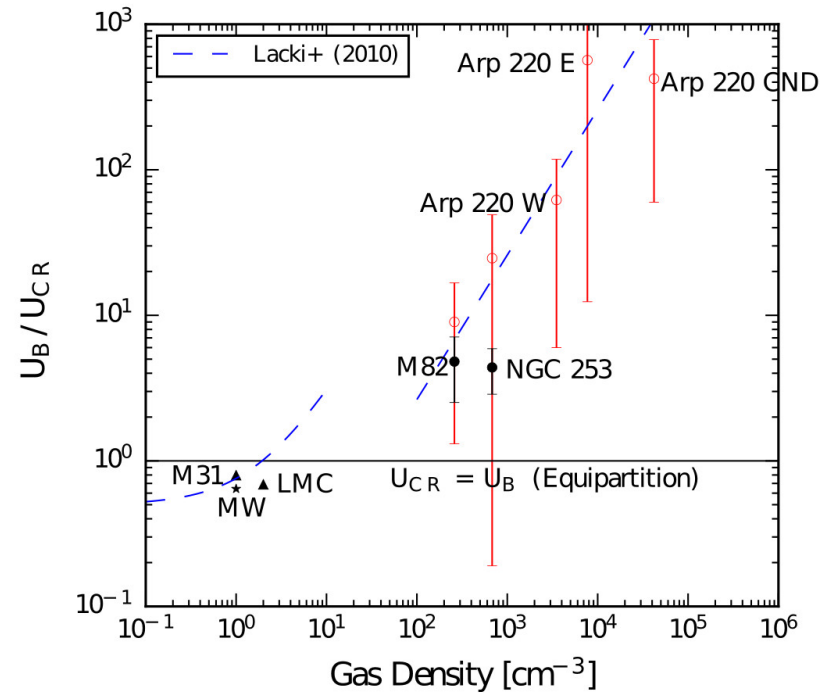
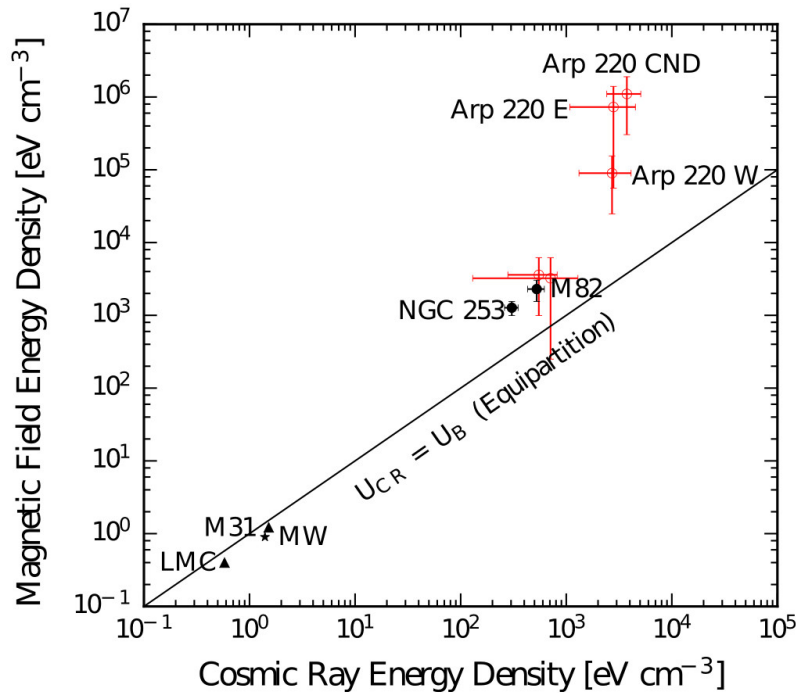
Rojas-Bravo & Araya 2016
MNRAS, 463

Central Molecular Zones

- Any process that causes disk matter to lose angular momentum sends it inwards; *the GC is always accreting gas* (at some level)
- In particular, the non-axisymmetric bar potential torques gas inwards
- ~5% of the Galaxy's H_2 is located in the GC

Energy Density Relations

Yoast-Hull+ 2016, MNRAS, 457, L29



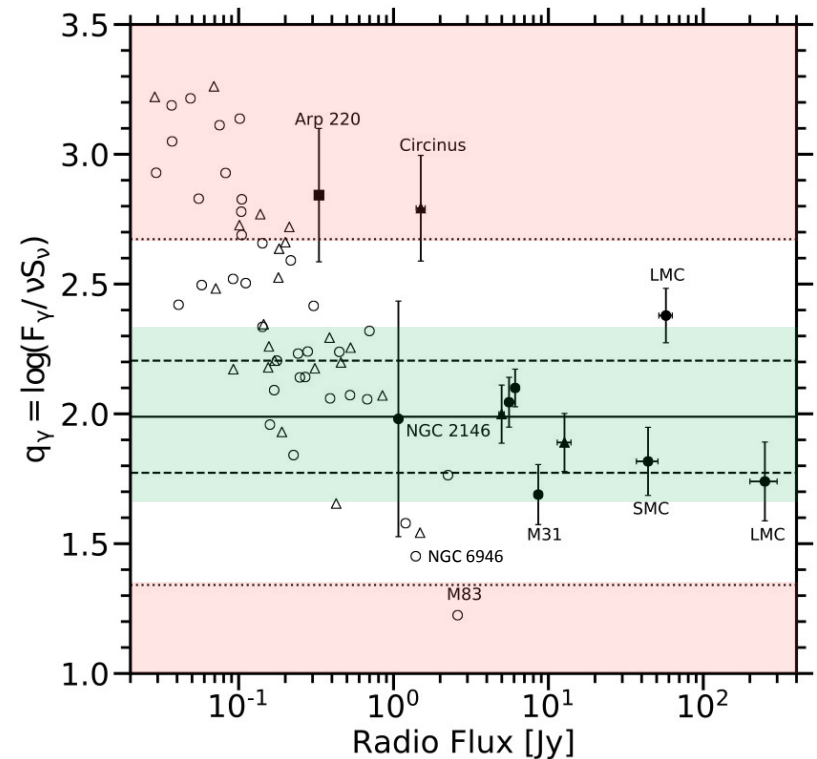
$$U_{CR} = \int E N(E) dE$$

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

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

Radio & γ -Ray Connections

- Most star-forming galaxies have clear correlation between radio + gamma-rays.
- Critical to get non-thermal radio flux (no free-free).
- Outliers:
 - gamma-ray bright / radio dim sources:
Arp 220, Circinus
 - gamma-ray dim / radio bright sources:
M83, NGC 6946



Yoast-Hull+ 2018

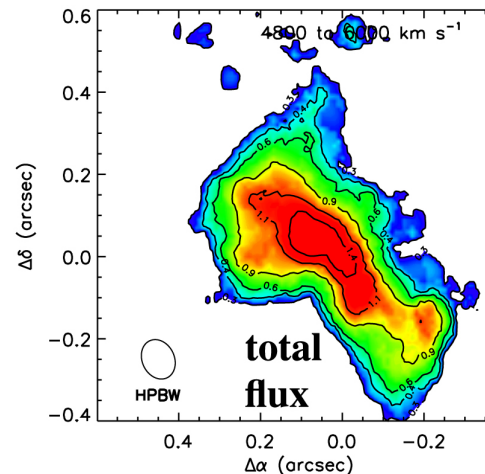
○ / △ = gamma-ray upper limit

IV. Complications- Hidden (Non-Jetted) AGN

Essential Properties of Arp 220

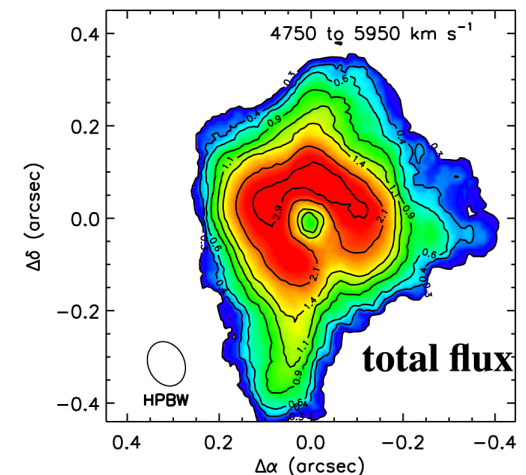
- Closest Ultra-Luminous Infrared Galaxy (ULIRG)
- Late stage merging galaxy
 - Two nuclei separated by $\sim 1'' \sim 370$ pc.
 - Nuclei are embedded in counter-rotating disk
- ISM properties:
 - $L_{\text{FIR}} \sim 10^{11.5-12.5} L_{\odot} \sim 10^{45} \text{ erg/s}$
 - $M_{\text{H}_2} \sim 10^9 M_{\odot}$
 - $B \sim \text{few mG}$

Arp 220 East CO (1-0)



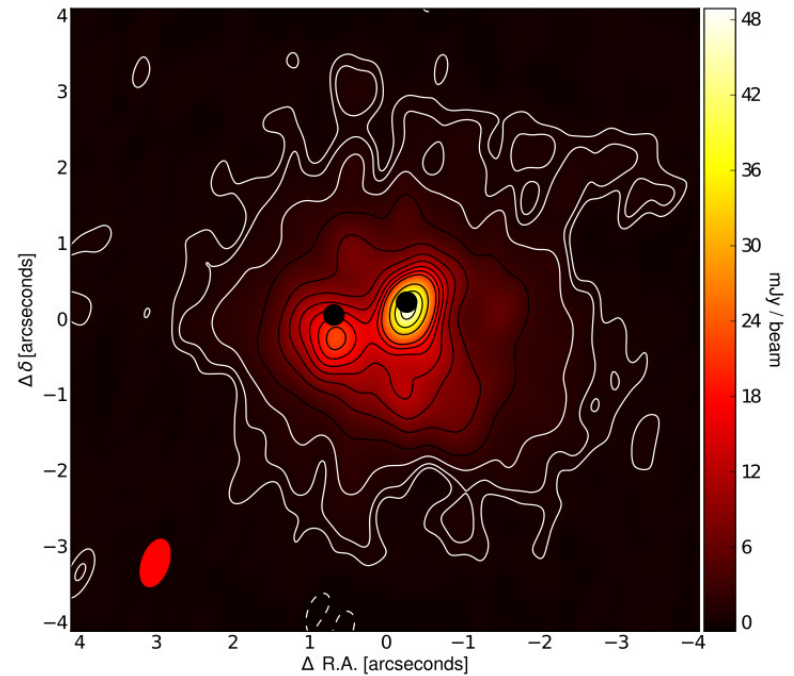
Scoville+ 2017
ApJ, 836, 66
ALMA Band 3

Arp 220 West CO (1-0)



The Central Nuclei of Arp 220

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



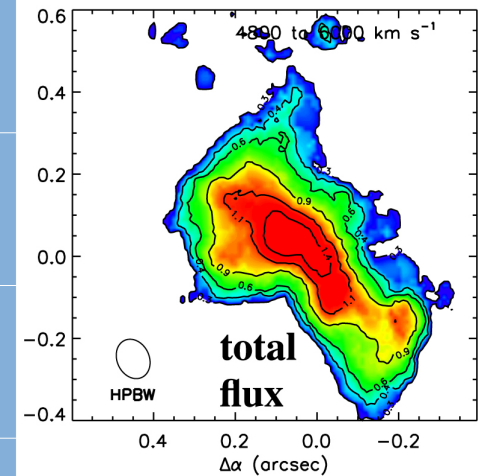
Varenius+ 2016,
A&A, 593, 86
LOFAR 150MHz

Arp 220 Nuclear Properties

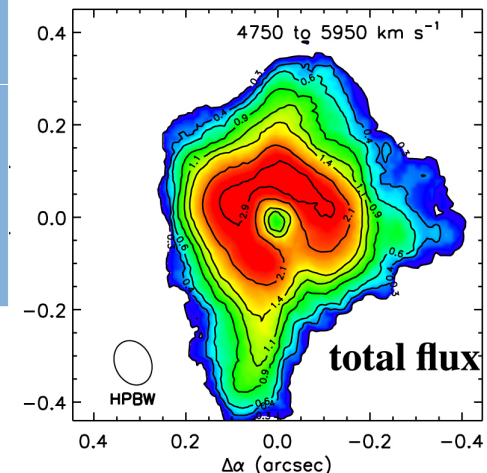
	East	West	CND
Radius (pc)	85	65	15
SN Rate (yr ⁻¹)	0.7	0.7	1.4
FIR Luminosity (L _⊙)	3×10^{11}	3×10^{11}	6×10^{11}
Molecular Mass (M _⊙)	10^9	6×10^8	6×10^8

Yoast-Hull & Murray
2018, in prep

Arp 220 East CO (1-0)

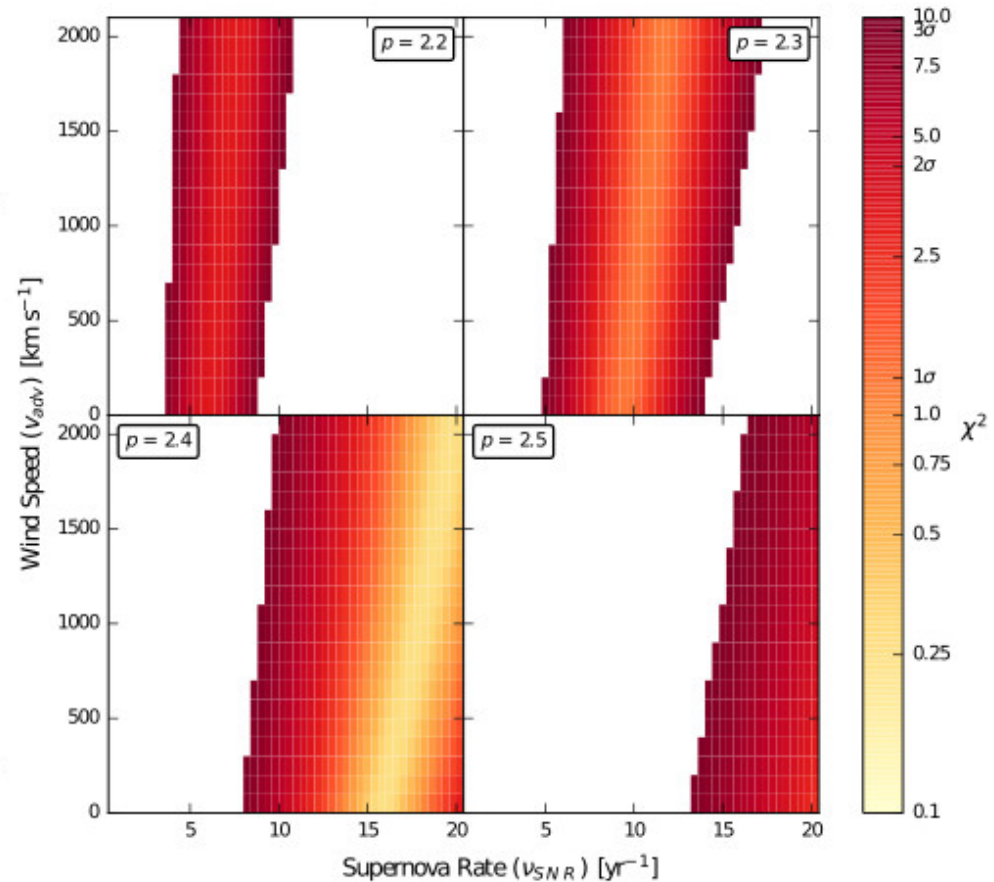
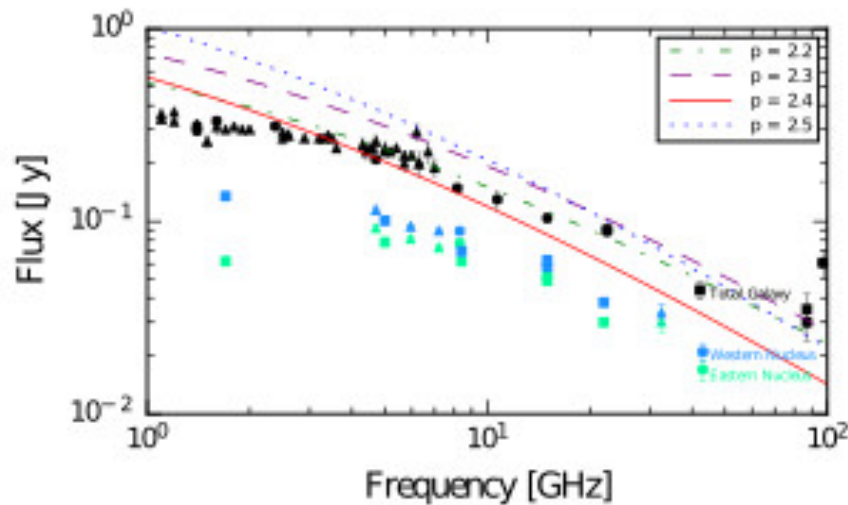
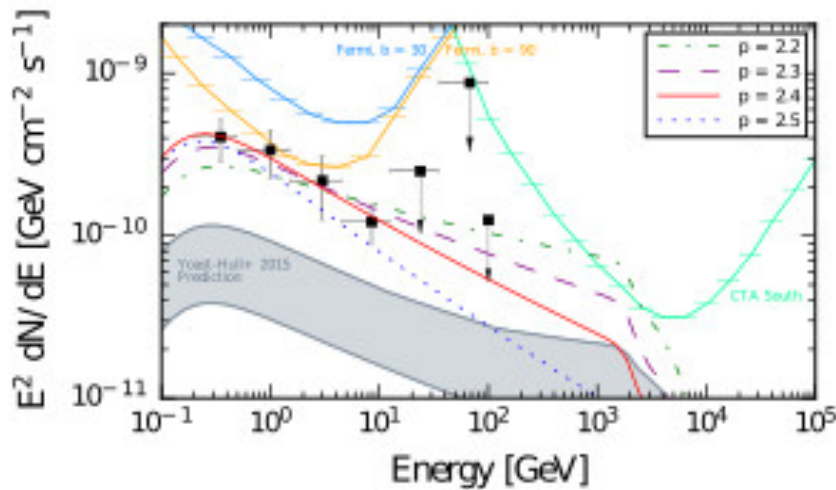


Arp 220 West CO (1-0)

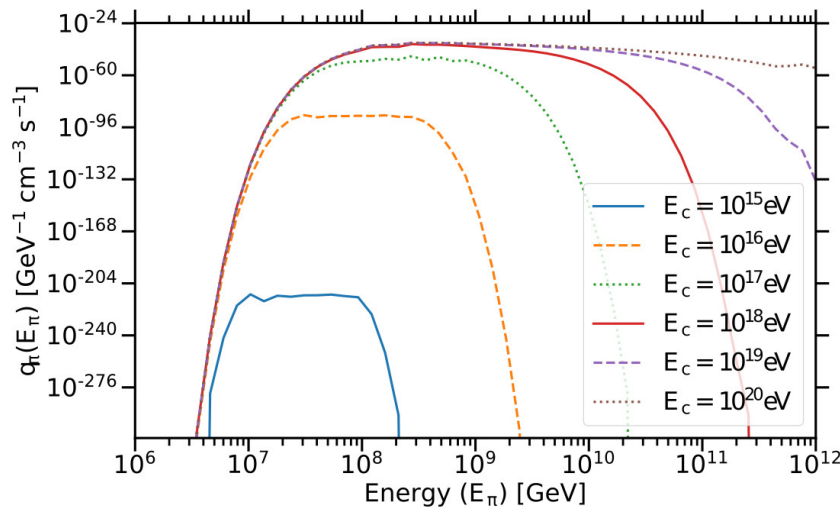
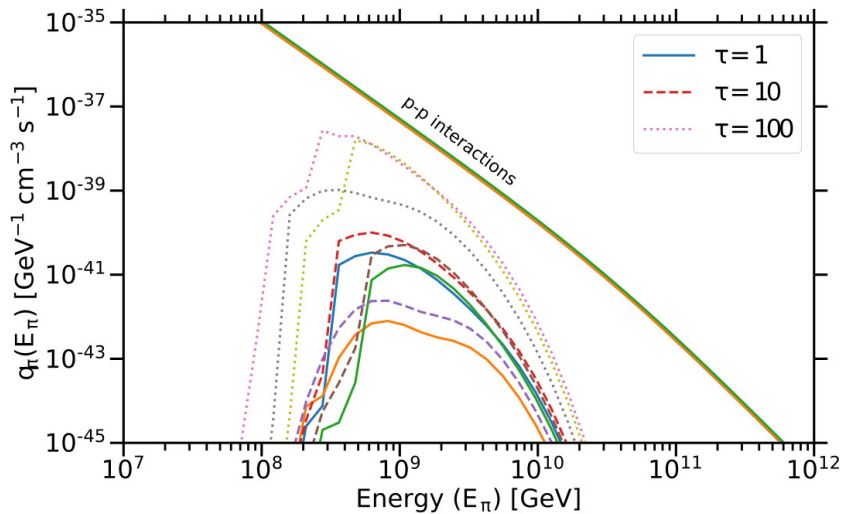


Gamma-Ray Implications

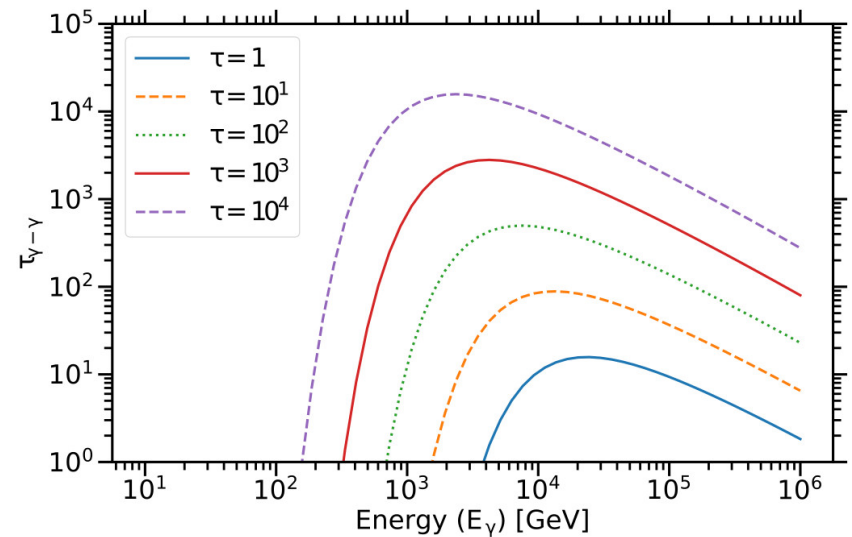
Yoast-Hull+ 2017,
MNRAS, 469L, 89



Other Interactions with Radiation



Yoast-Hull & Murray
2018, in prep



Parametrizations from:
Hümmer+ 2010, ApJ (p- γ)
Dermer & Menon 2009 (γ - γ)

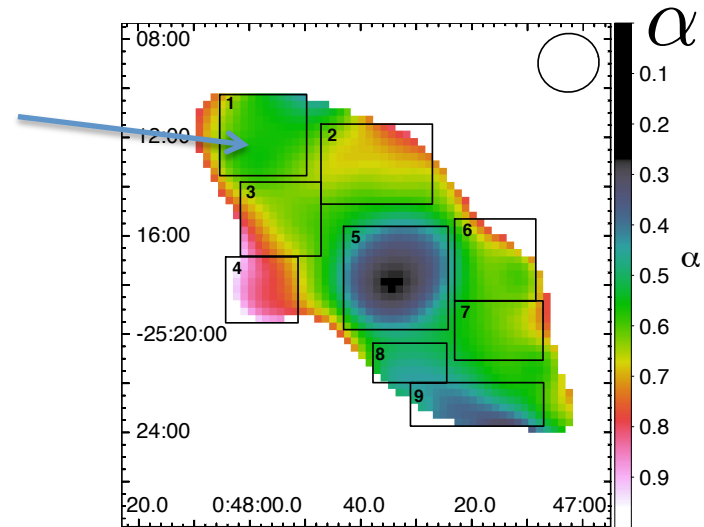
NGC 253 On Small and Big Scales

$$E_{\gamma} \frac{dN}{dE_{\gamma}} \propto E_{\gamma}^{\alpha}$$

$$E_e \frac{dN}{dE_e} \propto E_e^{-s}$$

$$\alpha = -s/2$$

$$s \approx 2.2$$



Kapinska+, ApJ 838 (2017)

IV. Separating Radio & Gamma-Ray Emission

Cosmic Ray Leptons

$$j_{\nu}^{Sy}(\nu) = \int dE_e N_e(E_e) \times P_{\nu}^{Sy}(E_e)$$

Lower B

Lower $N(E)$

$$P_{\nu}^{Sy}(E_e) \propto U_B \beta_e^2 \gamma_e^2 \frac{\nu^{1/3}}{\nu_c^{4/3}} e^{-\nu/\nu_c}$$

$$N_e(E_e) = q_e(E_e) \times t(E_e)$$

Lower $t(E)$

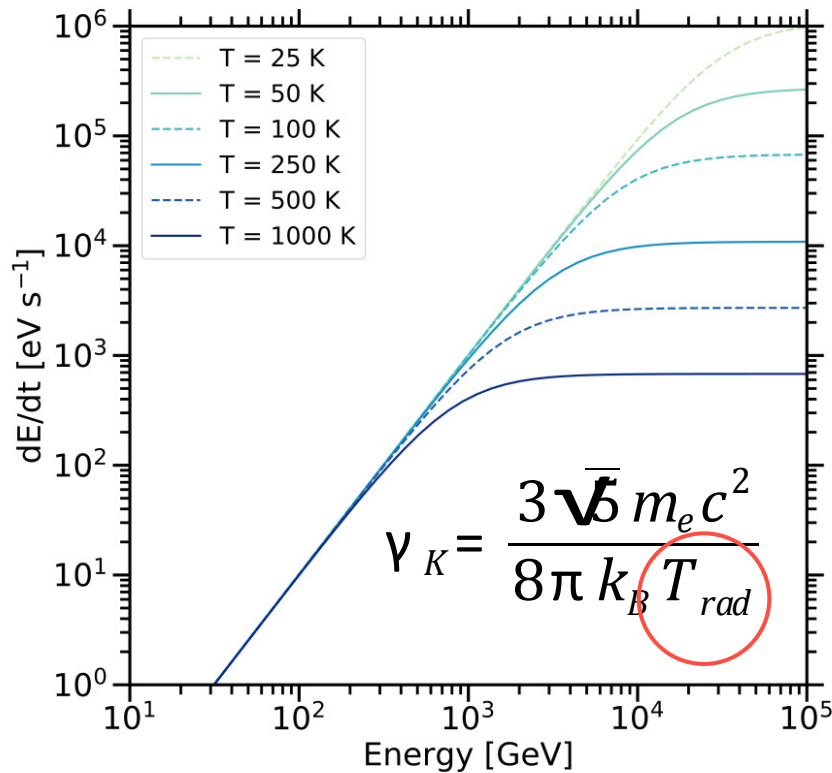
$$q_e(E_e) = q_e^{prim}(E_e) + q_e^{sec}(E_e)$$

$$t_e(E_e)^{-1} = t_{loss}(E_e)^{-1} + t_{adv}^{-1}$$

Cannot lower $q(E)$!

Yoaast-Hull & Murray
2018, in prep

Lepton Energy Losses



Yoast-Hull & Murray
2018, in prep

$$\left(\frac{dE}{dt}\right)_{Ion} = \frac{9}{4} m_e c^3 \sigma_T n_{mol} (6.85 + \ln(\gamma_e))$$

$$\left(\frac{dE}{dt}\right)_{Br}^{ion} = \frac{3\alpha}{2\pi} c \sigma_T n_{ion} Z(Z+1) E_e (\ln(2\gamma_e))$$

$$\left(\frac{dE}{dt}\right)_{Br}^{mol} = \frac{3.9\alpha}{8\pi} c \sigma_T \varphi_{HI}^{s-s} n_{mol} E_e$$

$$\left(\frac{dE}{dt}\right)_{IC} = \frac{4}{3} c \sigma_T U_{rad} \frac{\gamma_K^2 \gamma_e^2}{\gamma_K^2 + \gamma_e^2}$$

$$\left(\frac{dE}{dt}\right)_{Sy} = \frac{4}{3} c \sigma_T \frac{B^2}{8\pi} \gamma_e^2$$

Observational Constraints

$$n_{mol} = \frac{M_{mol}}{2 m_p \mu_{mol} V}$$

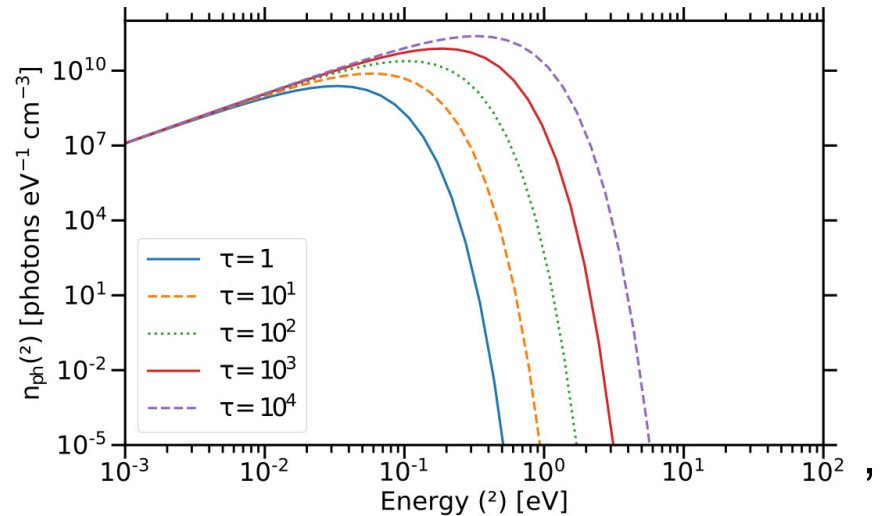
obs. limit

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

obs. limit

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

obs. limit



$$L_{Bol} \approx \text{few} \times 10^{12} L_{\odot}$$

e.g. Wilson+ 2014,
ApJ, 789, L36

But: optical depth!

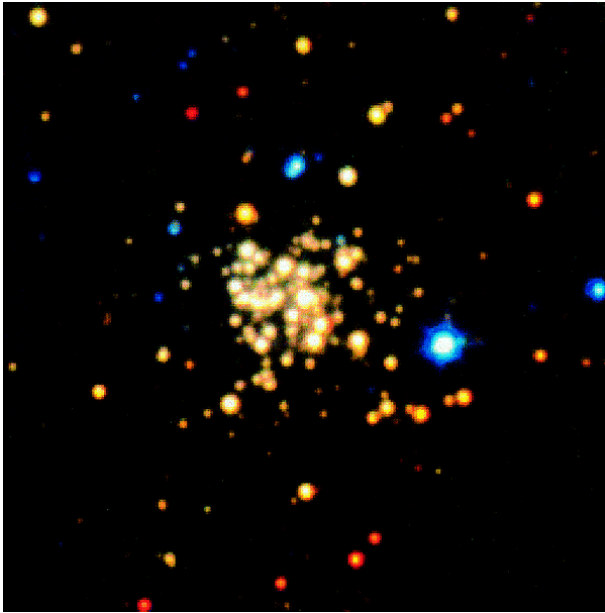
$$U_{rad} = \tau U_{eff}$$

$$T_{rad} = \tau^{1/4} T_{eff}$$



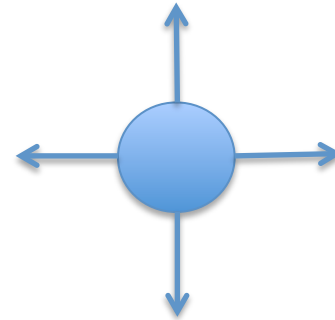
Galactic Center- A Little Starburst Region

Stellar Cluster 25 pc from
Galactic Center



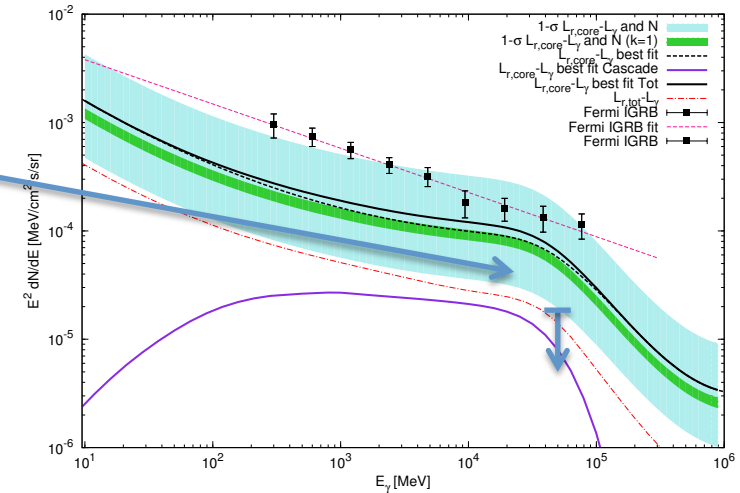
Serabyn +, Nature 394 (1998)

Note- WR stars have a lifespan of $\sim 10^{6.5-7}$ Myrs



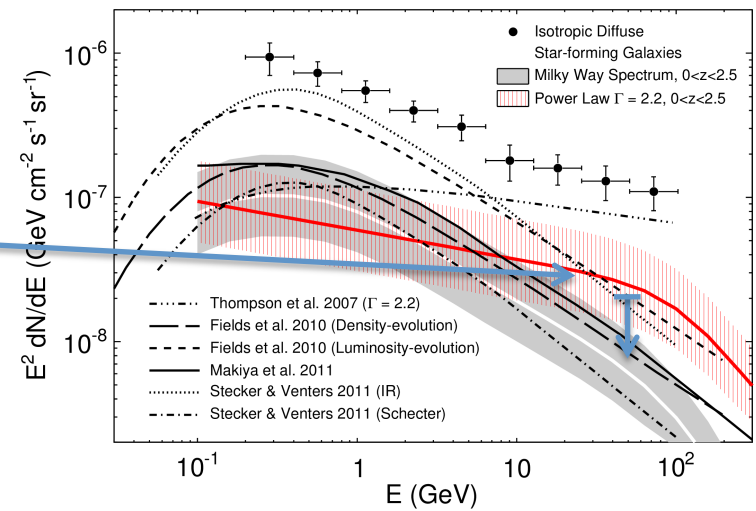
Still Non-Blazar & Starburst Galaxy Contributions Not Removed

Radio Galaxy contributions are estimated to make up a significant fraction of the remaining IGRB.



Di Mauro et al. 2013 (1304.0908)

Contribution from lower energy (< 10 PeV) CRs in starburst galaxies



Ackermann et al. 2012 (1206.1346)