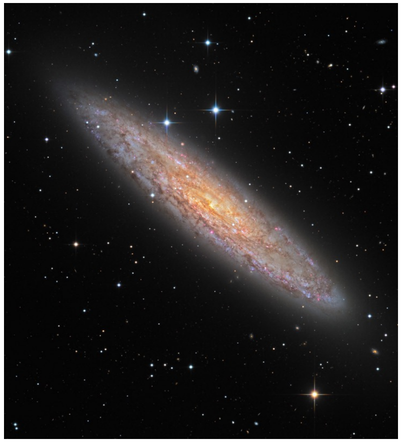
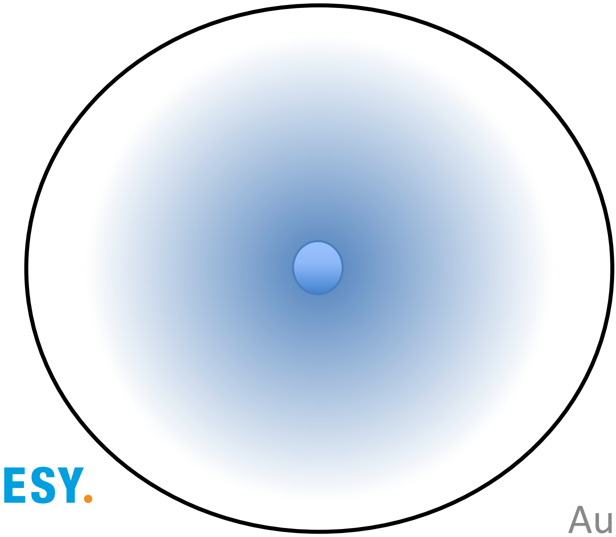
Cosmic Ray Energy Losses within Galaxies

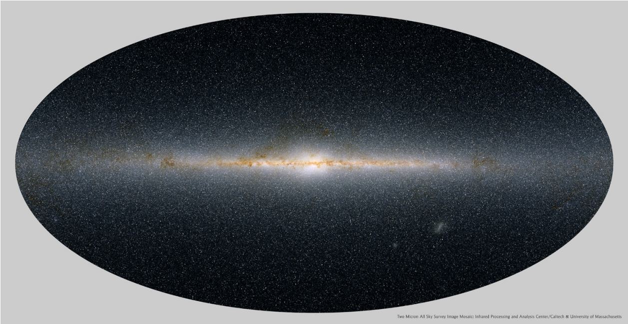
Discovered in optical by Caroline Herschel in 1783



Starburst Galaxy: NGC 253

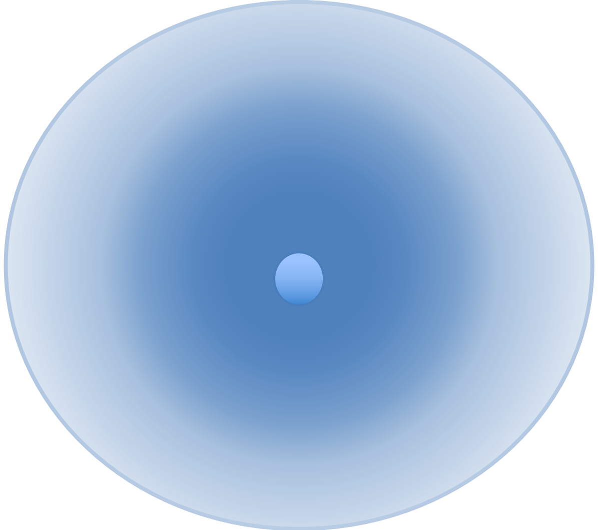


2005- 2MASS



Two Micron All Sky Survey Image Mosaic: Infrared Processing and Analysis Center/Caltech & University of Massachusetts

Milky Way

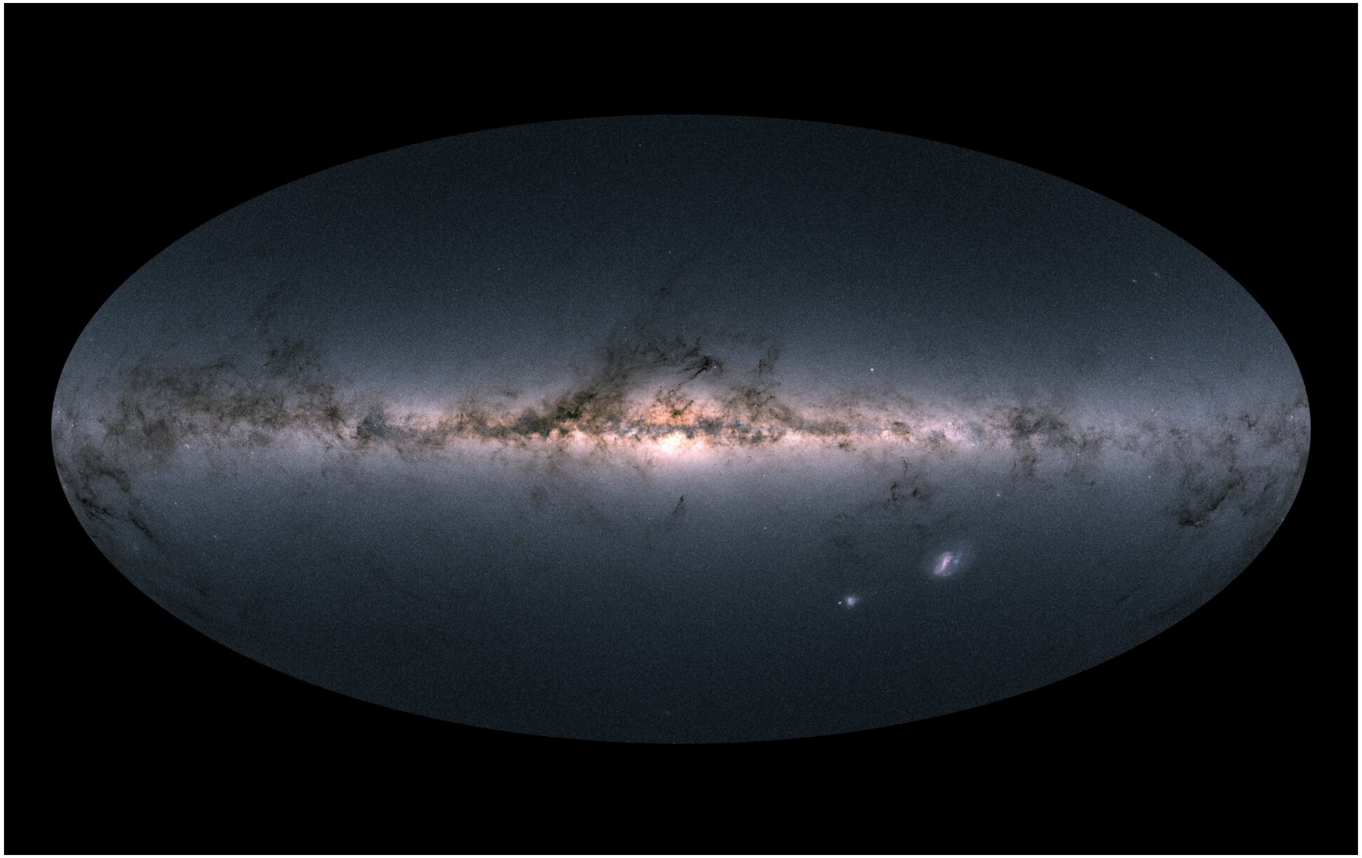


DESY.

August, 2024

Milky Way (also shown in Francis Halzen's talk)

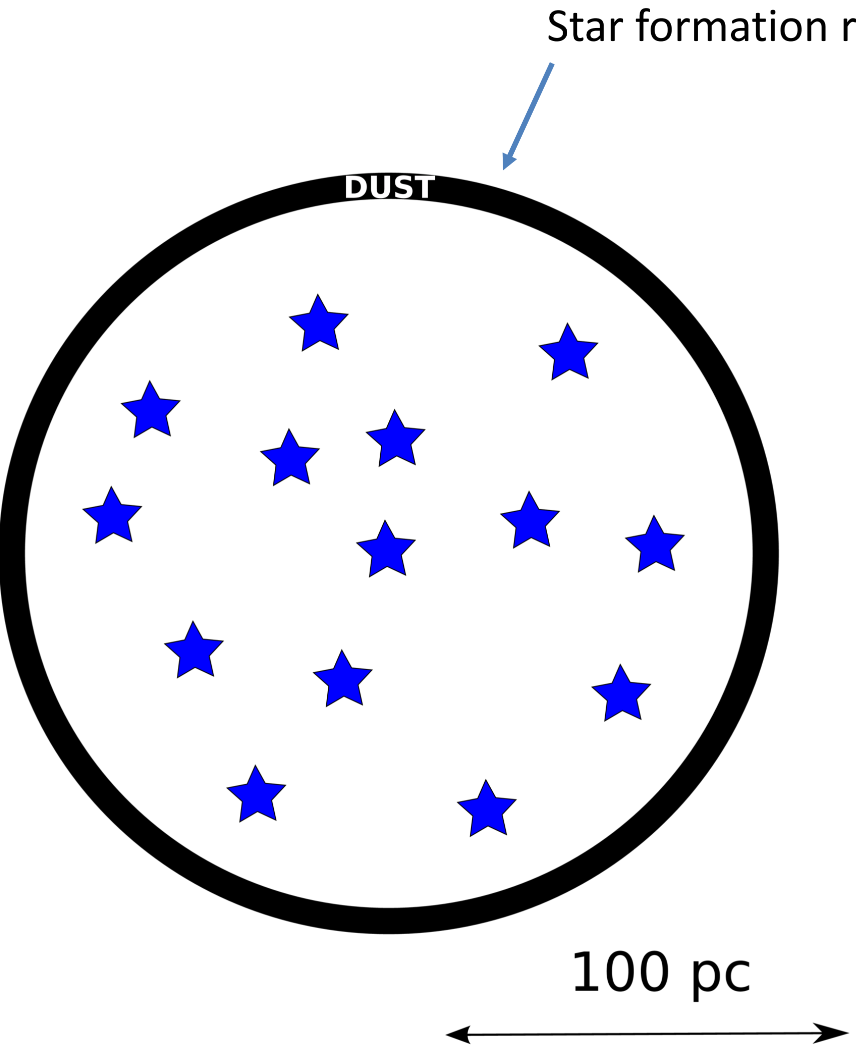
2018- GAIA

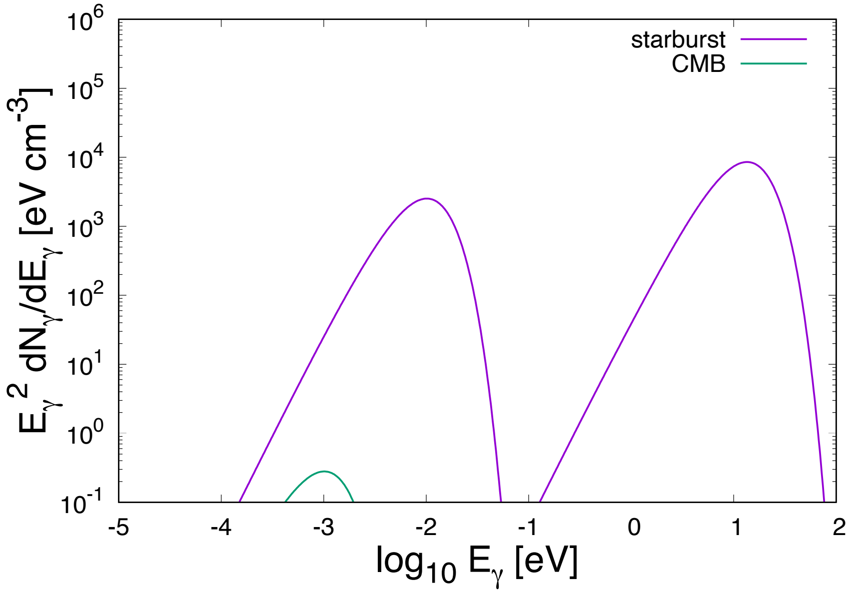


Milky Way

Galactic Thermal Emission

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

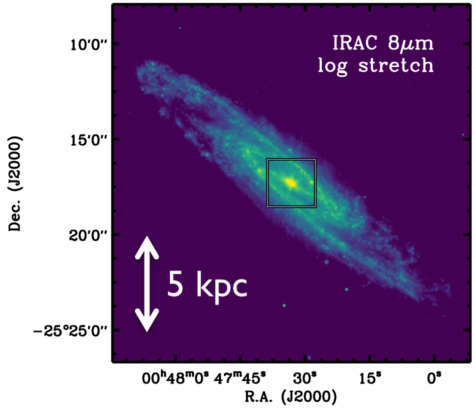
50% of the star formation occurs in the Galactic nucleus of NGC 253

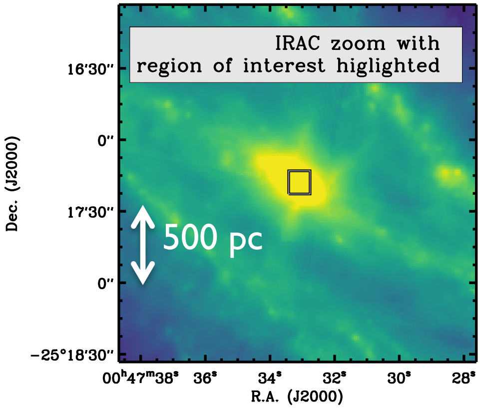
Nuclear star-formation rate:

$$\sim \mathbf{2\ M_{\odot}\ yr^{-1}}$$

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

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

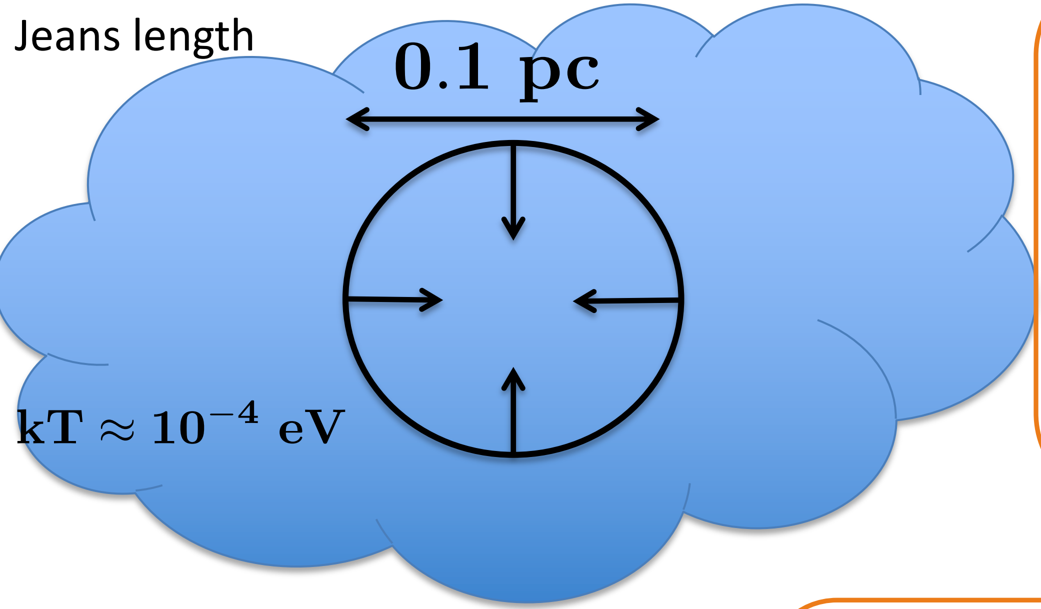




A. Leroy+ 2018

Star Formation Regions

Star Formation is Bursty

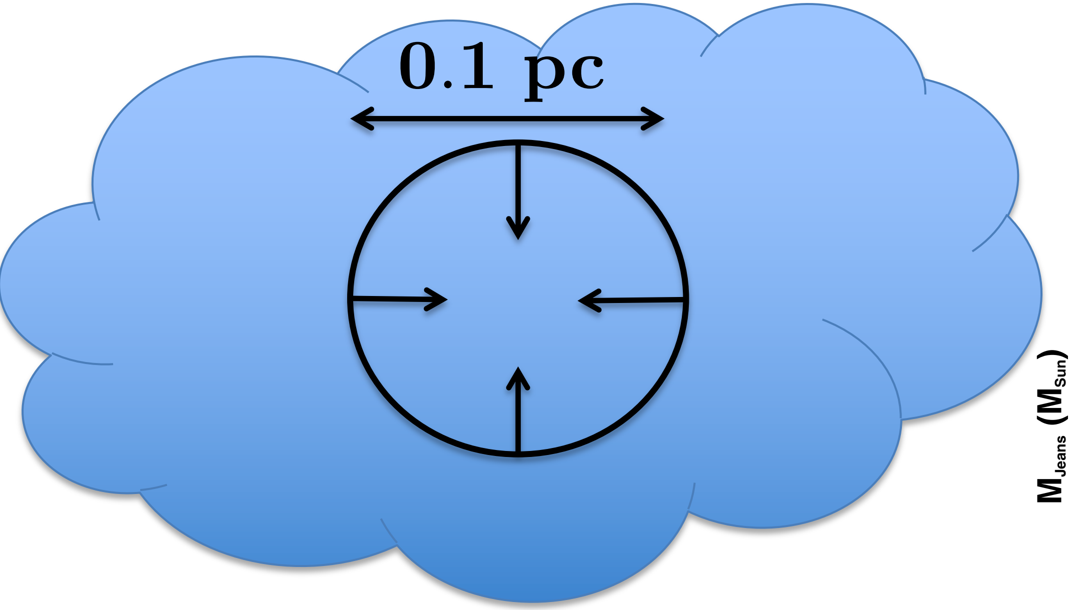


$$t_{\rm ff} \approx \left(\frac{r^3}{GM}\right)^{1/2} \approx \left(\frac{10^4\ \mathrm{cm}^{-3}}{n}\right)^{1/2}\ \mathrm{Myr}$$

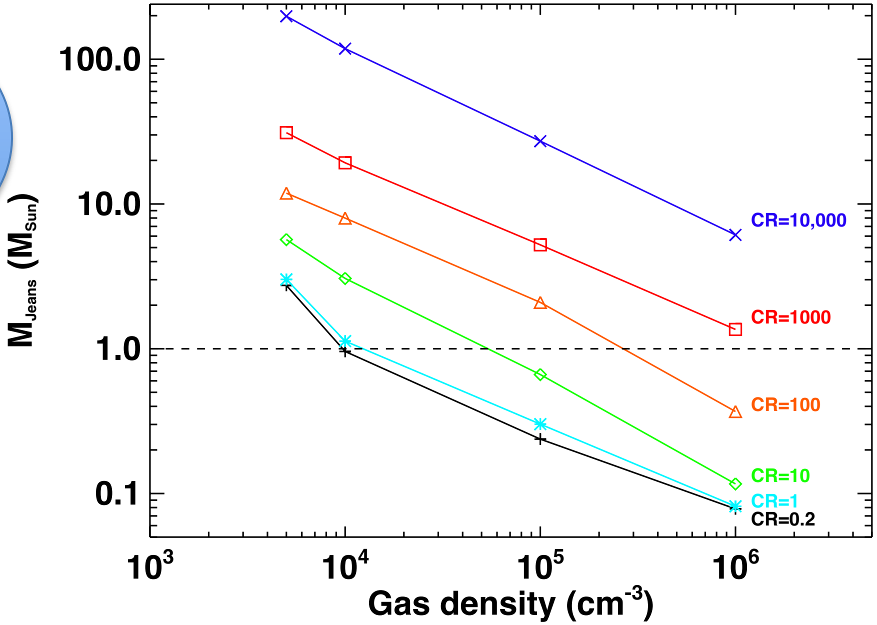
$$\beta_{\rm th} = \left(\frac{kT}{m_p c^2}\right)^{1/2} \approx 10^{-6.5}$$

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

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

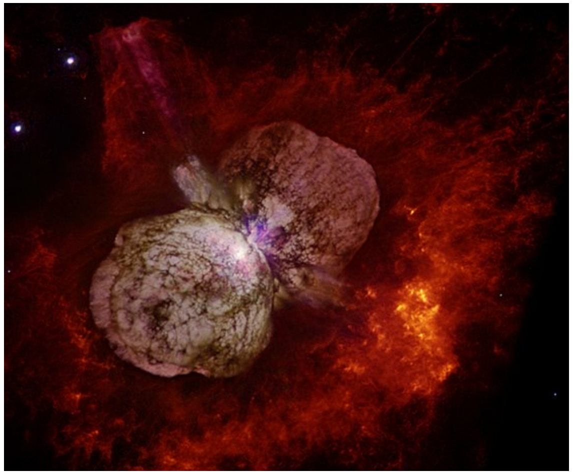


Papadopoulos+ MNRAS, 414 (2011)

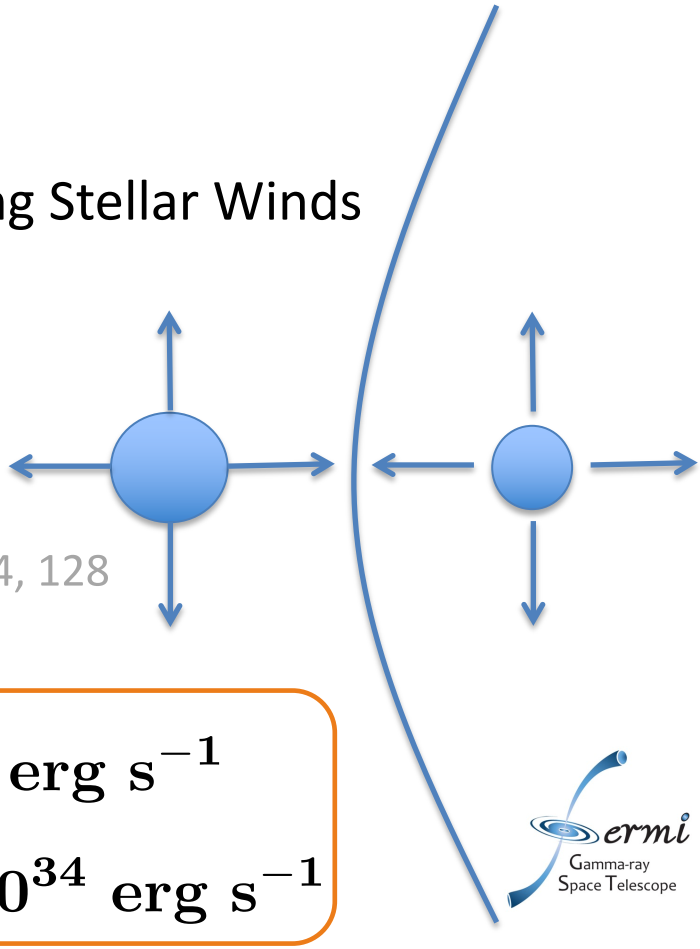
Evidence for Non-Thermal Particles On Small Scales?

Particle Acceleration in Stellar Winds

Hubble Image of Eta Carina

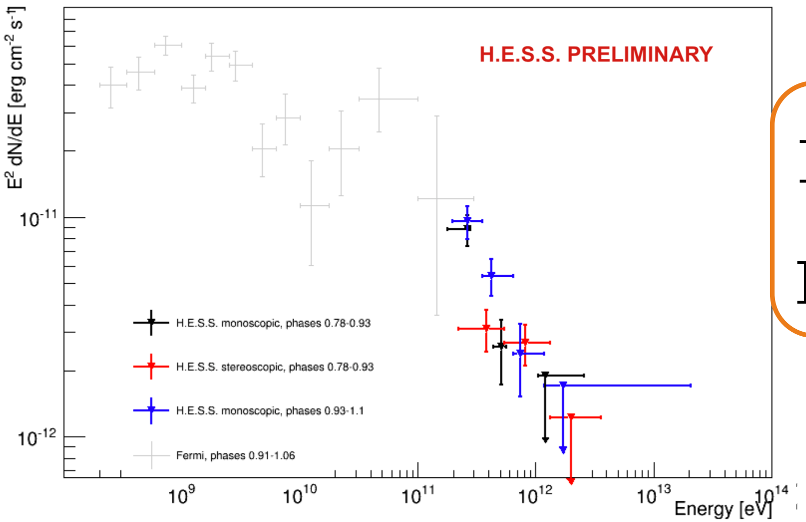


2) Colliding Stellar Winds



Spectrum

Abramowski A. et al., 2012, MNRAS, 424, 128



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

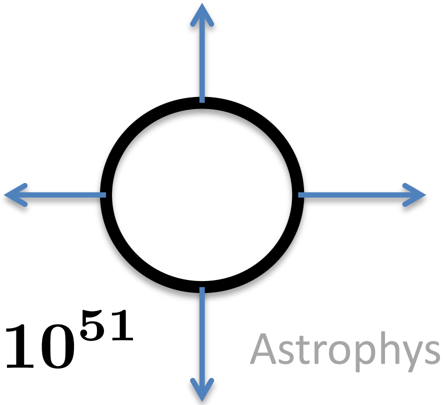
$$\mathbf{L_{\gamma}^{GeV} \approx 3 \times 10^{34}\ erg\ s^{-1}}$$

Close-ish to calorimetric regime

Particle Acceleration by Supernova Shocks

What acceleration source/process is at play?

1) SNR blastwave

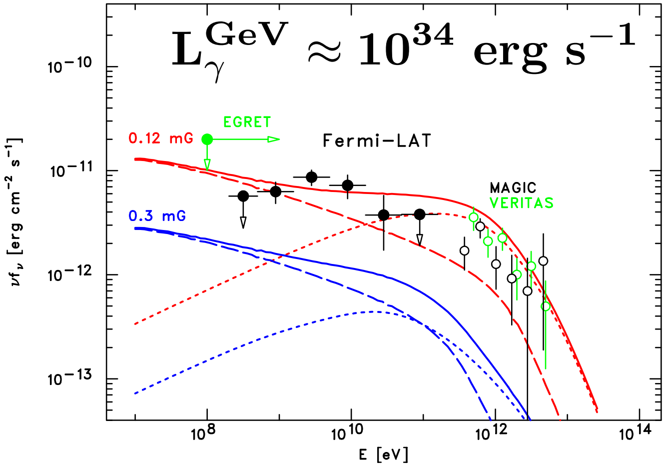


$$\mathbf{E_{KE} \approx 10^{51}}$$

Hershel/Hubble Image

Astrophysical Journal, 894, 2020

Spectrum

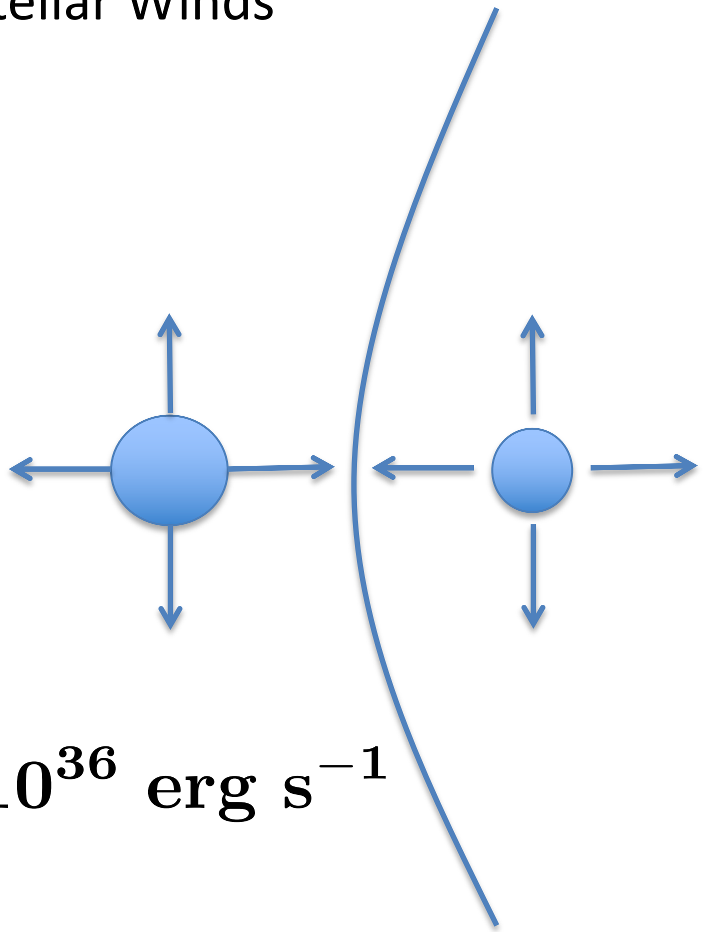


Note- not acting as a calorimeter (on source scales at least)

Particle Acceleration in Starburst Systems

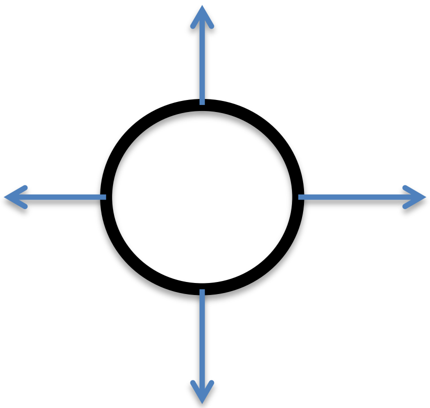
What acceleration source/process is at play?

1) Colliding Stellar Winds



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

2) SNR blastwave

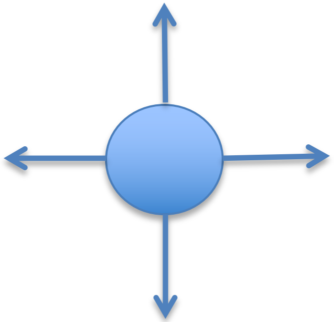


$$\mathbf{E_{KE} \approx 10^{51}}$$

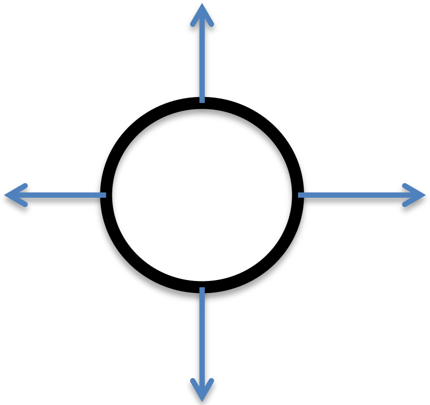
Averaged over 1000 yrs (the Sedov time) this amounts to a mean KE luminosity of $\mathbf{L_{KE} \approx 3 \times 10^{40}\ erg\ s^{-1}}$

Galactic KE Luminosity from All Colliding Wind Binaries and SNR

1) Colliding Stellar Winds



2) SNR shock



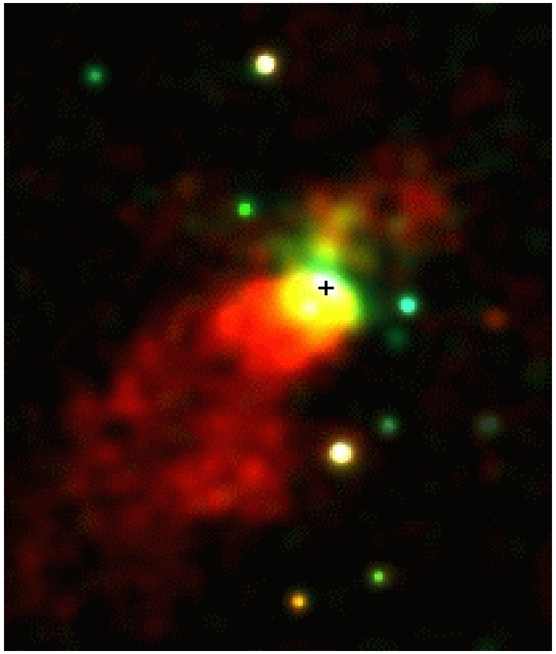
$$\langle L_{\mathrm{wind}} \rangle \approx 10^{39}\ \mathrm{erg\ s^{-1}}$$

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

Where Does this Energy Injected Into Cosmic Rays Go?

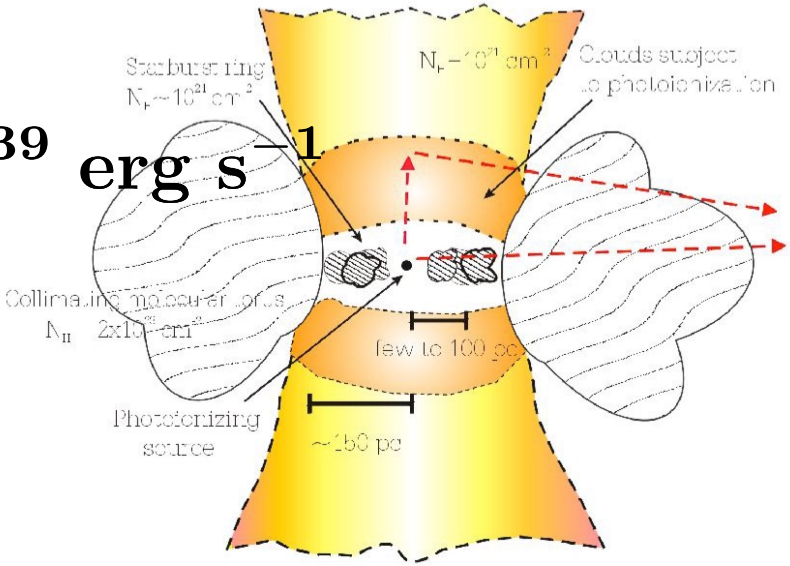
Galactic Center Outflow (NGC 253)

Chandra X-ray observations of the nucleus



1.4 kpc x 1.6 kpc

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



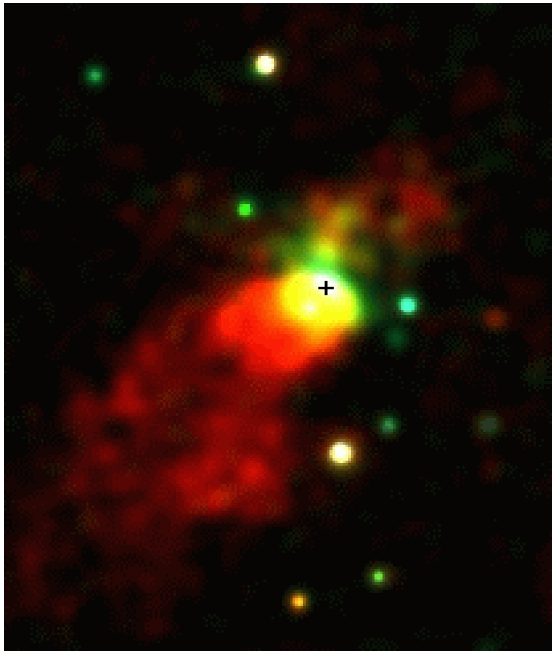
Weaver, K. +, Ap.J. 576 (2002)

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

Galactic Center Outflow (NGC 253)

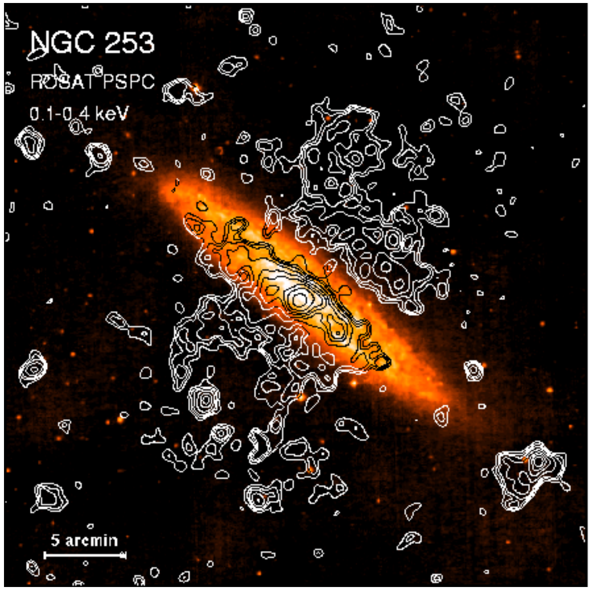
Pietsch+ A&A, 360, 24 (2000)

Chandra X-ray observations of the nucleus



1.4 kpc x 1.6 kpc

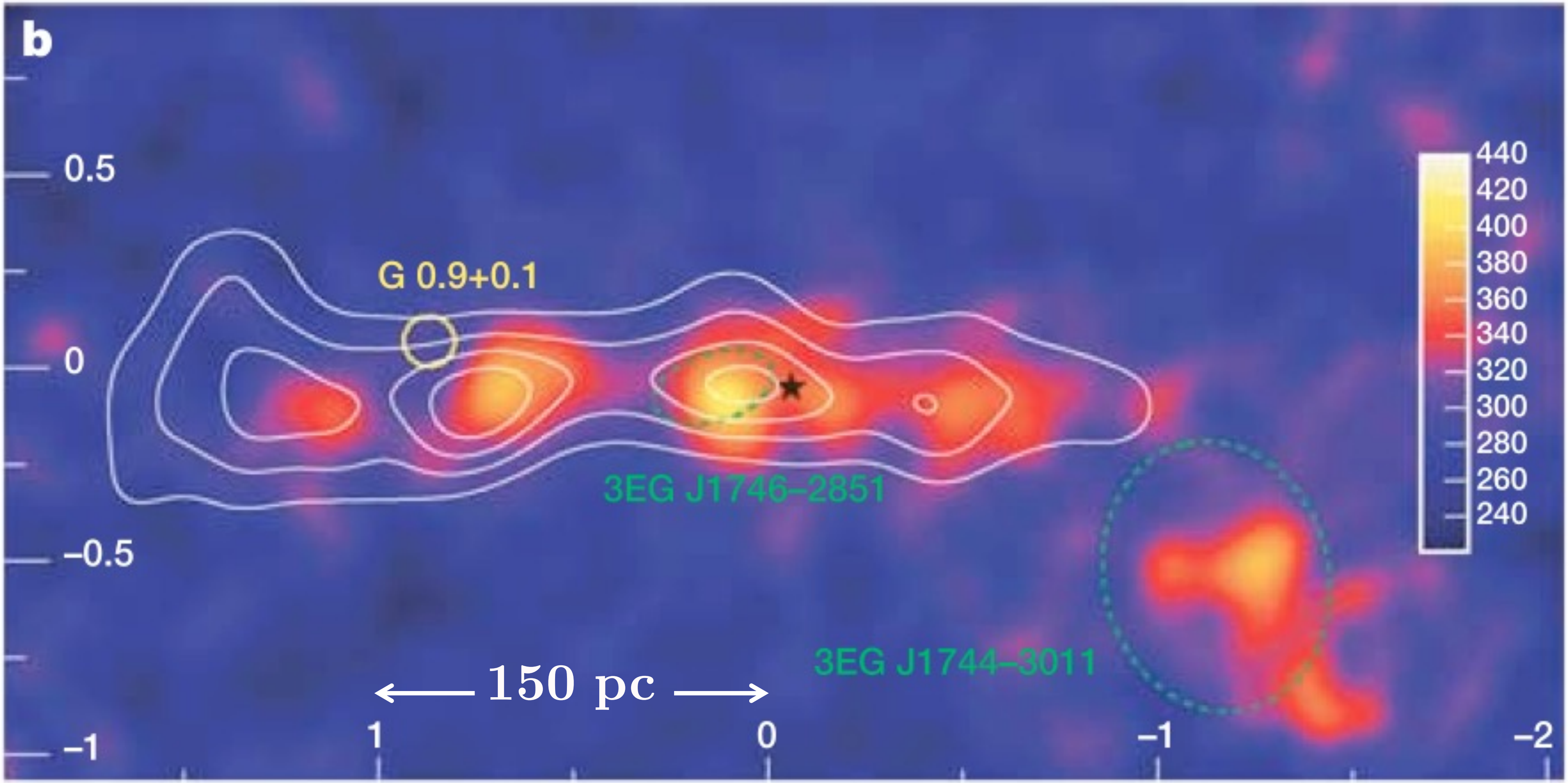
$$L_{X-ray} \approx 10^{39}\ \mathrm{erg\ s^{-1}}$$



DESY.

Milky Way- Galactic Center Outflow

Contours indicate density of molecular gas, traced by CS line emission

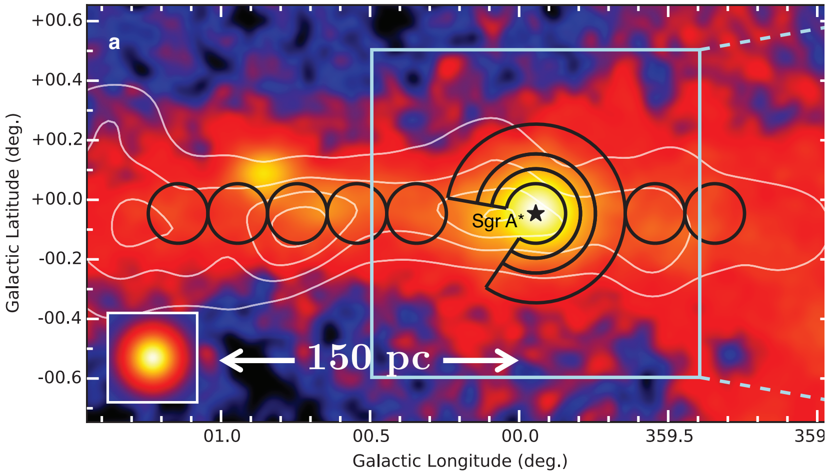


$$\mathrm{L}_\gamma(1\ \mathrm{TeV}) \approx 5 \times 10^{34}\ \mathrm{erg\ s}^{-1} \qquad \mathrm{L}_\gamma^{\mathrm{IR}} \approx 10^{42}\ \mathrm{erg\ s}^{-1}$$

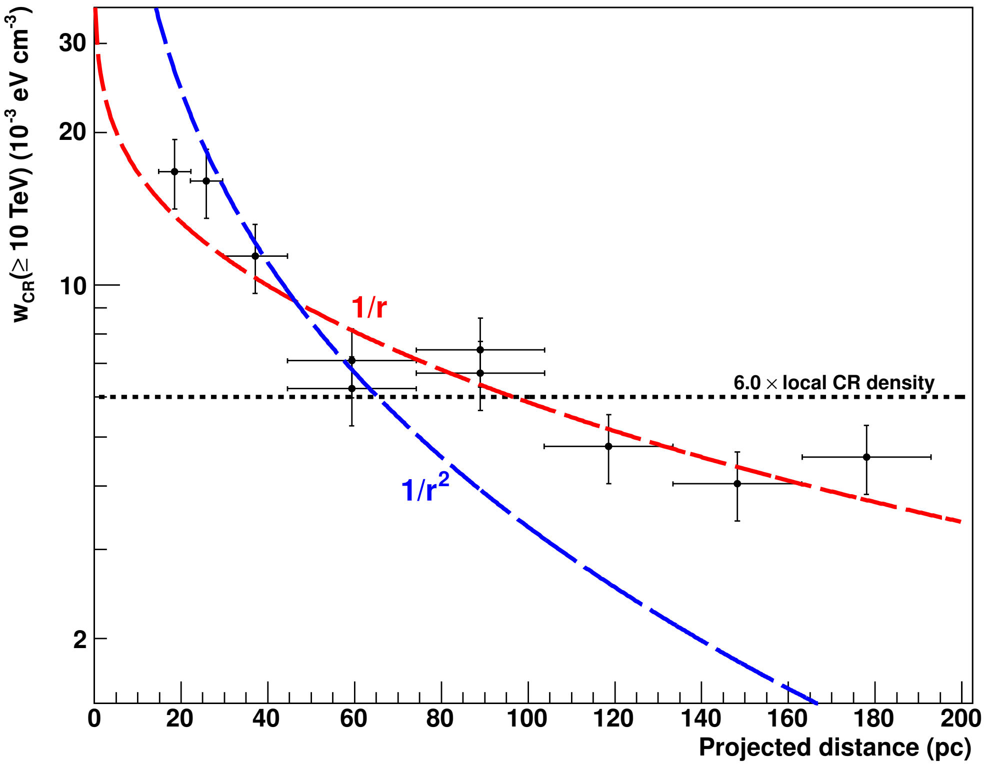
$$\dot{\mathrm{M}} \approx 0.1\ \mathrm{M}_\odot\ \mathrm{s}^{-1}$$

Aharonian+, Nature, 439, 695 (2006)

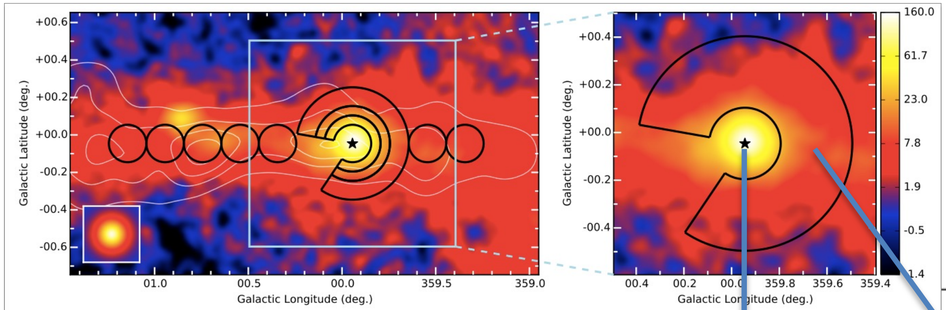
Milky Way- The Galactic Center Lit Up By Cosmic Rays



Aharonian+, Nature 531, 476 (2016)



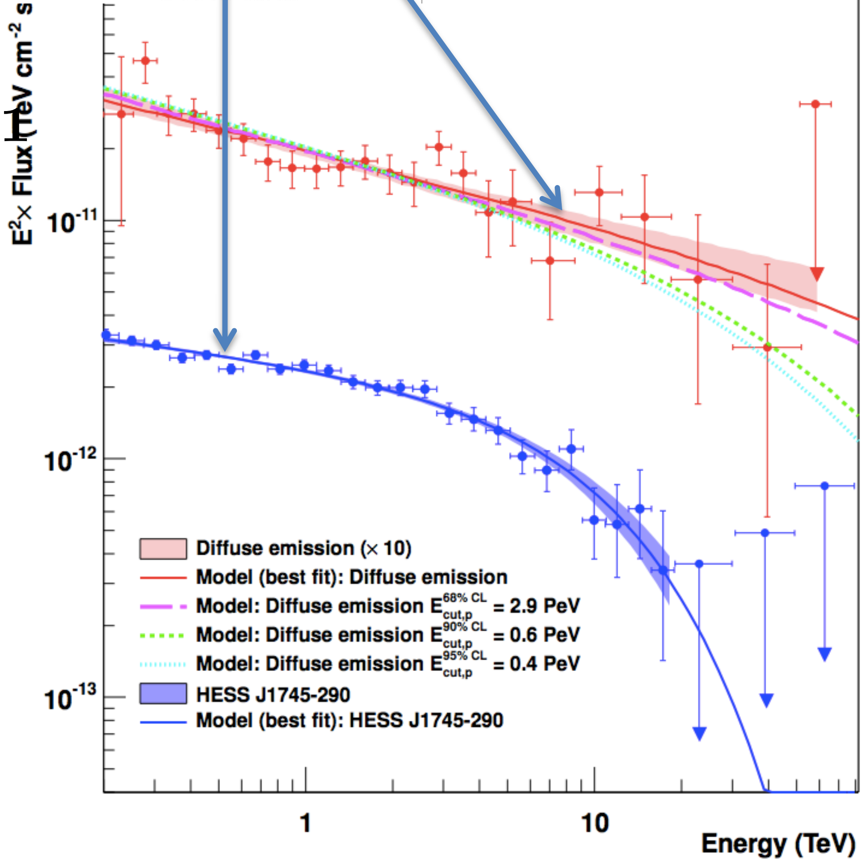
Milky Way- The Galactic Center Lit Up By Cosmic Rays



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

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

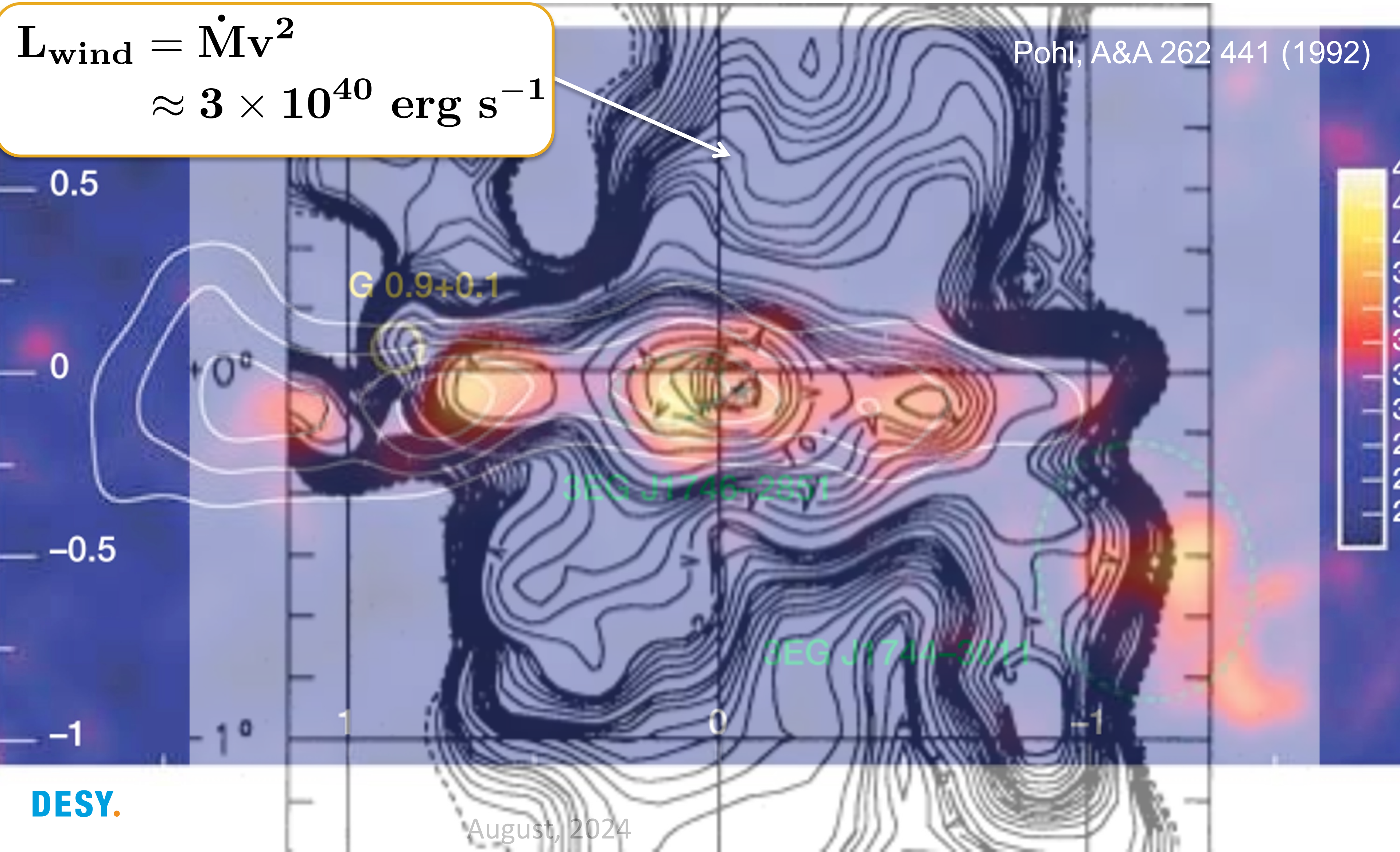
Note- not acting as a calorimeter (on these scales at least)



Milky Way- Galactic Center Outflow

Radio contours are shown

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

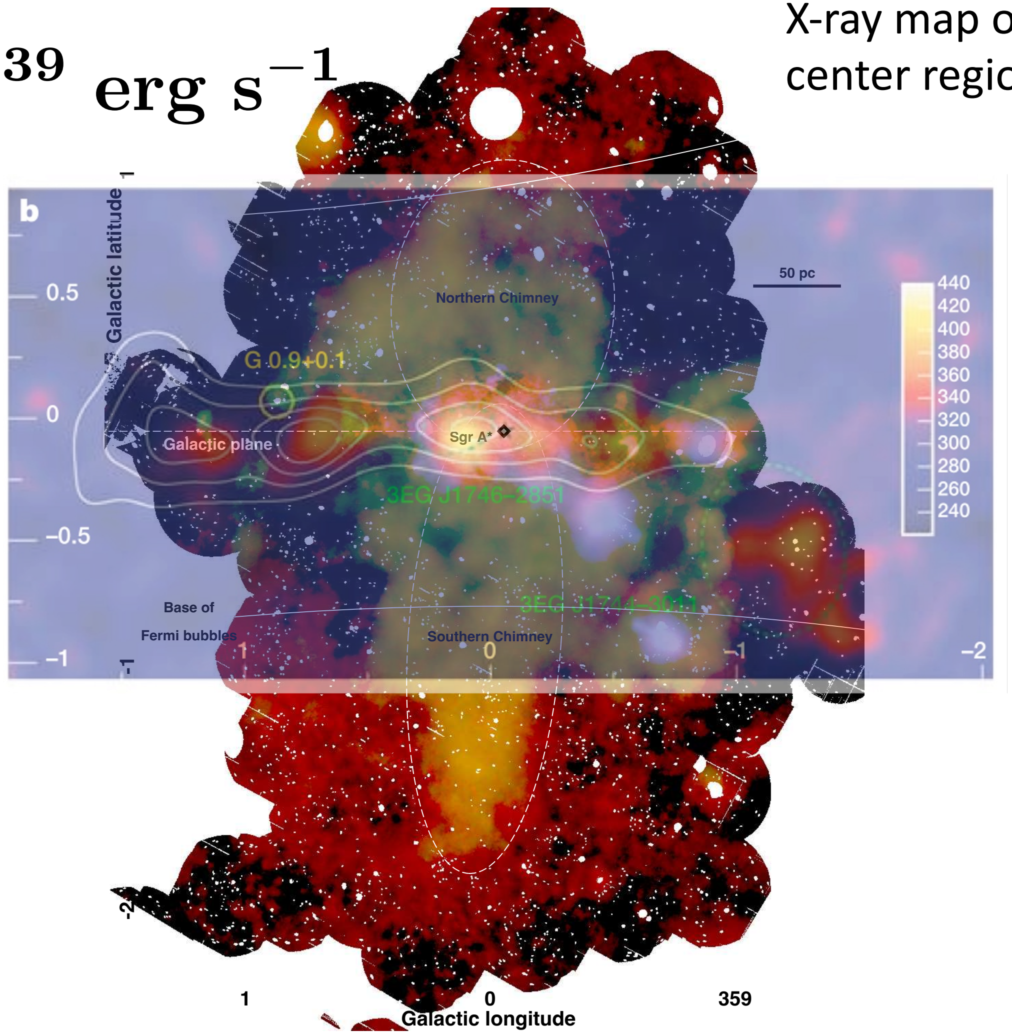


Pohl, A&A 262 441 (1992)

Milky Way- Galactic Center Outflow

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

X-ray map of Galactic center region



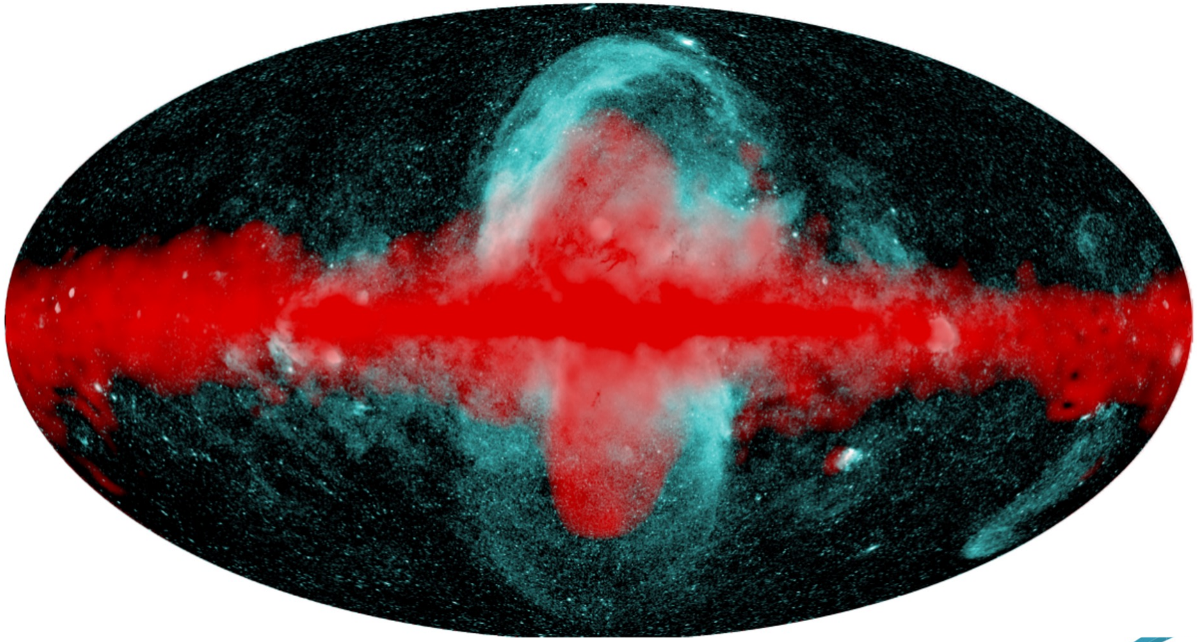
Nature 567, pages 347 (2019)

Milky Way- Galactic Center Outflow

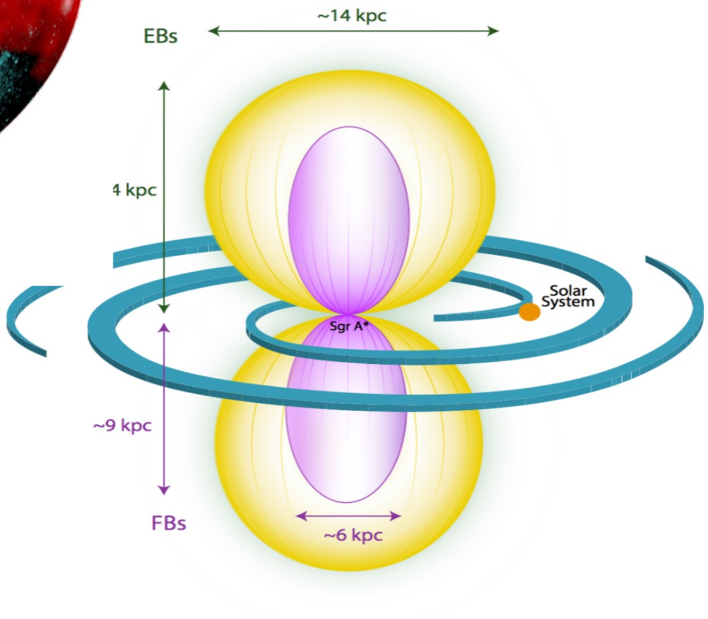
Bubble Emission: $\mathbf{L_\gamma(GeV) \approx 4 \times 10^{37}\ erg\ s^{-1}}$

$\mathbf{L_{X-ray} \approx 10^{39}\ erg\ s^{-1}}$

Fermi-LAT + eROSITA full sky map



Nature 588, 227 (2020)



Including the Galactic plane, this becomes:

$\mathbf{L_\gamma(GeV) \approx 10^{39}\ erg\ s^{-1}}$

At What Distance Scale is the Bulk of the Non-Thermal Energy Deposited?

Cooling Times

- Energy Loss Timescales

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

$$\mathbf{t_e(E_e) = \frac{1}{(4/3) c n_\gamma \sigma_T b}}$$

$$\mathbf{b = E_e E_\gamma / m_e^2}$$

$$\downarrow$$

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

Cooling Times

- Energy Loss Timescales

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

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

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

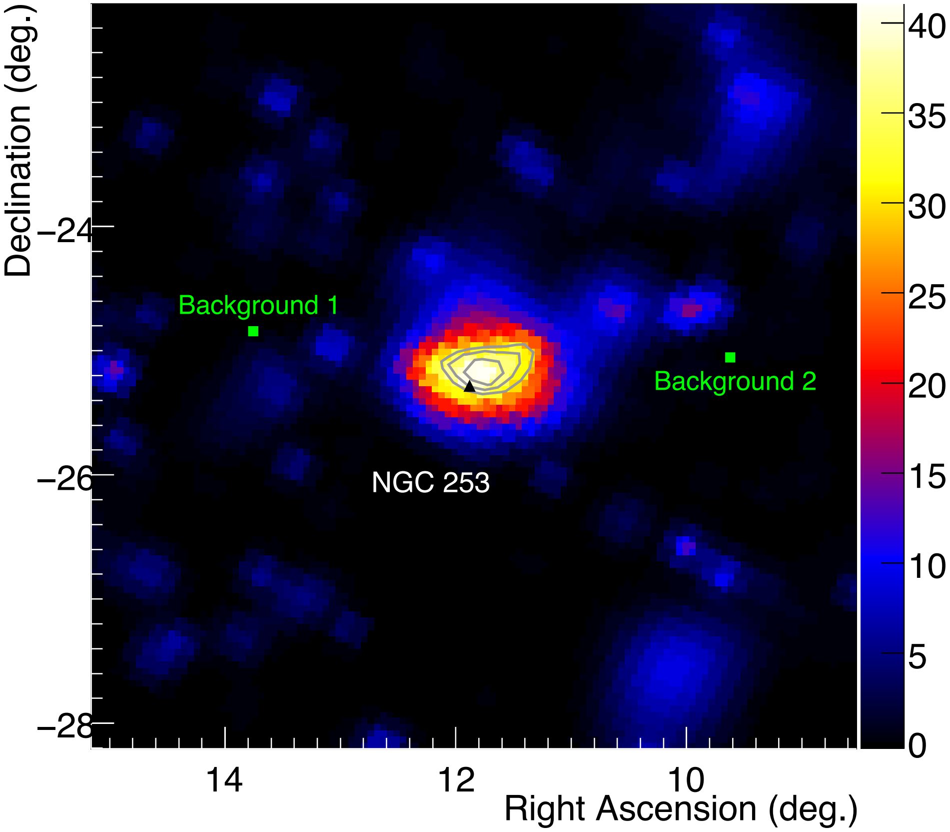
$$\mathbf{t_e = 10^5 \left(\frac{5\ GeV}{E_e}\right)\left(\frac{500\ eV\ cm^{-3}}{U_{\gamma/B}}\right)\ yrs}$$

NGC 253: Gamma-Ray Emission Perspective

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

Gamma-Ray Contour Map- rather poor spatial information

Fermi



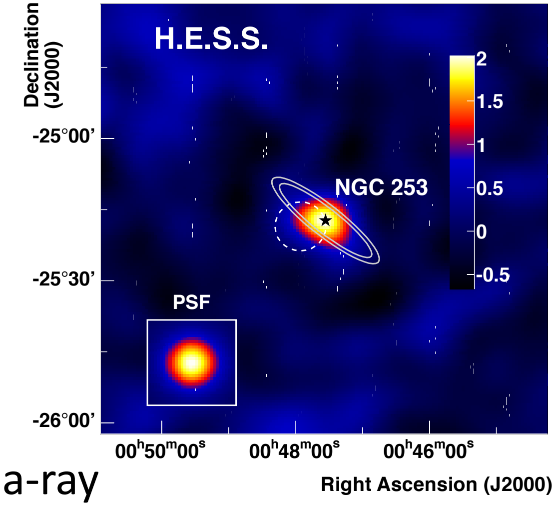
Abdo +, Ap.J. 709 (2010)

- 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 center (ie. Galaxy!)
- TeV observations constrain the emission region to be < 1.5 kpc from Galactic center (ie. Galactic Nucleus)

NGC 253: On Small and Big Scales

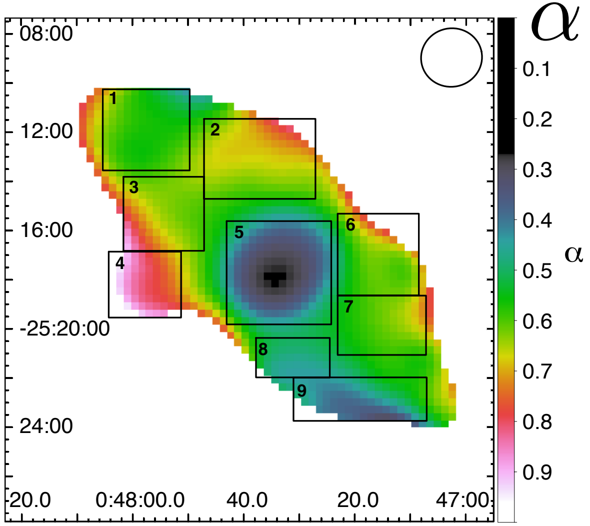
$$L_\gamma(\mathrm{TeV}) \approx 10^{39}\ \mathrm{erg\ s^{-1}}$$

Abramowski+, ApJ 757 (2012)



Small Scale

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



Big Scale (MWA)

How kind nature is to us!

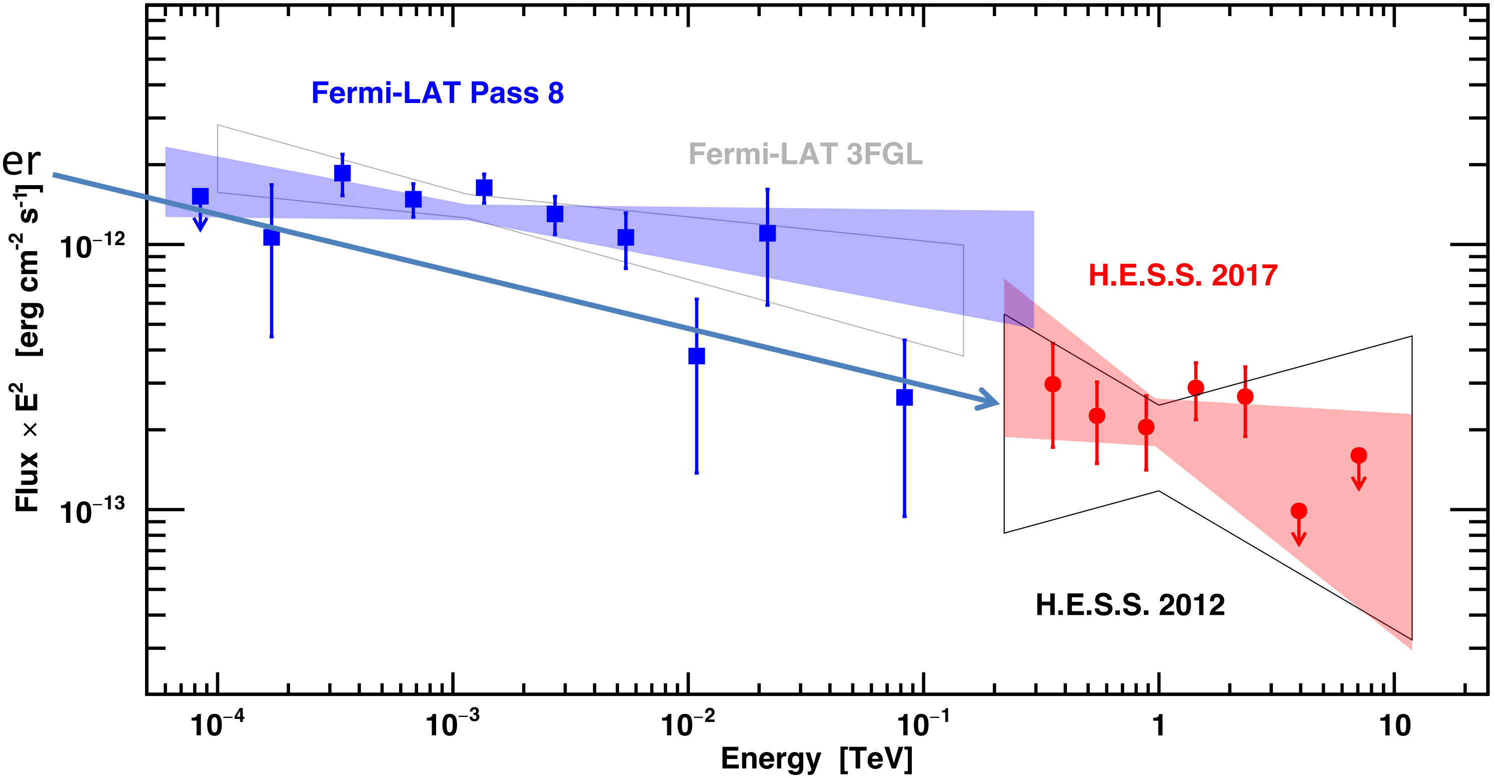
Kapinska+, ApJ 838 (2017)

NGC 253: Gamma-Ray Spectrum

Gamma-Ray Spectral Coverage-
very good energy information

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

Could there be larger scale diffuse emission that has been missed?



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

Calorimetric or Not Calorimetric?

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:

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

NGC 253: Gamma-Ray Perspective

- CR Luminosity from astrophysical parameters

Thin + Thick Target Spectra:

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

- Only two ways for particles to leave the box- die in it or escape from it.

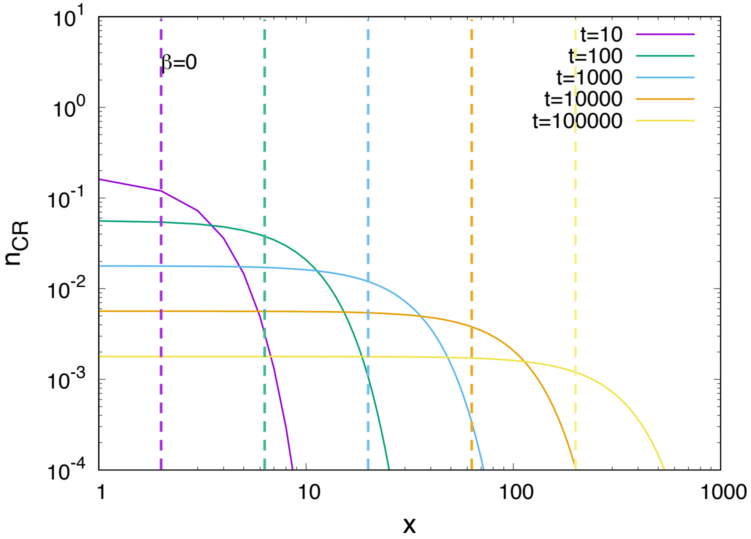
- The gas in the starburst as “Thin” or “Thick” target for the CRs, depending on which of the ways the CRs preferentially leave the system.

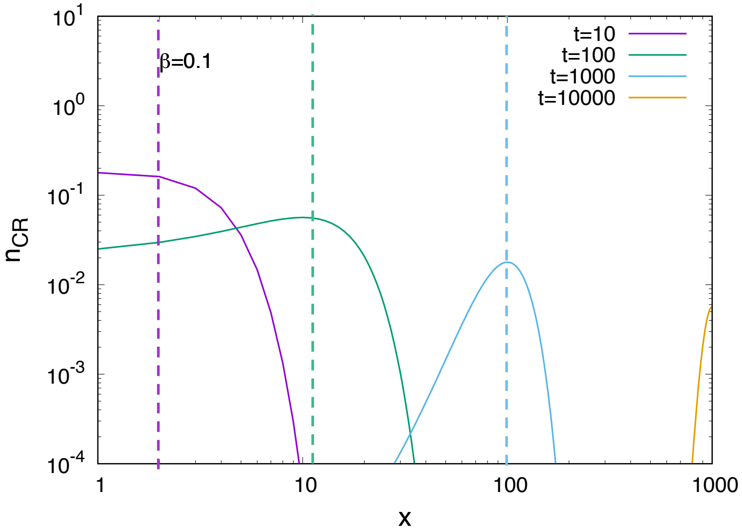
Dominant Transport Process?

Competition Between Diffusive and Advective Escape

Fokker-Planck Equation

$$\boxed{\frac{\partial \mathbf{n}}{\partial \mathbf{t}} = -\nabla \cdot (\mathbf{v}\mathbf{n} - \mathbf{D}\nabla\mathbf{n})}$$

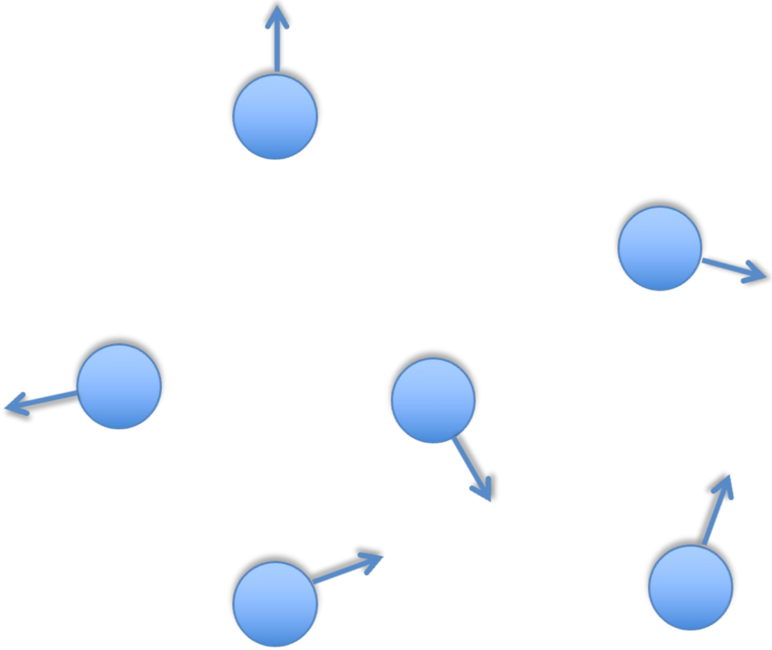




How Do Non-Thermal Particles Get Transported Out of the Central Region?

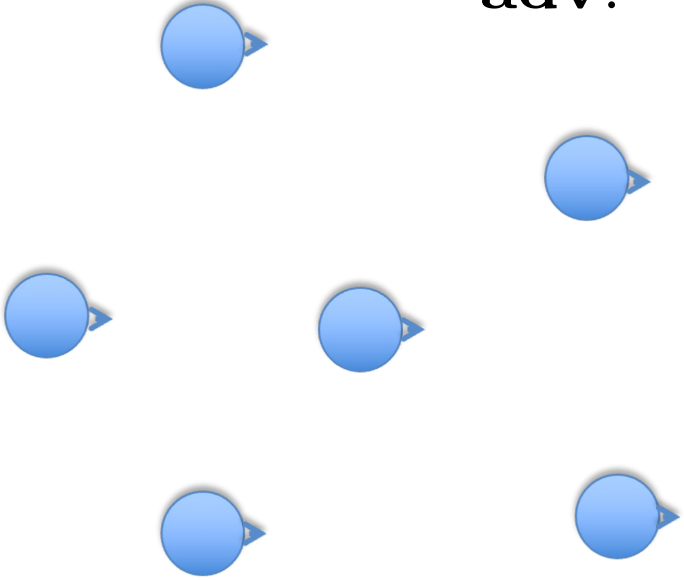
Diffusive Escape

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



Advective Escape

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



NGC 253: Transport Timescale

- Escape- Competing Transport Timescales

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

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

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

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

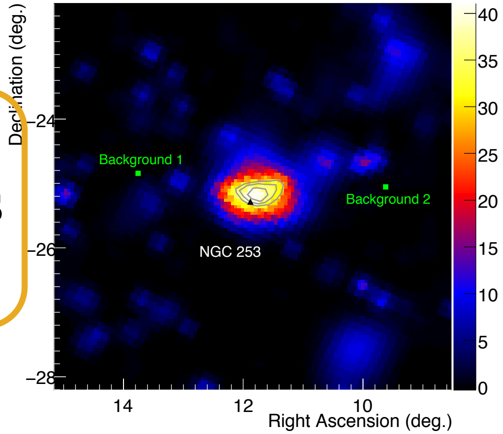
$$\mathbf{v_{adv.} \approx 300\ km\ s^{-1}}$$

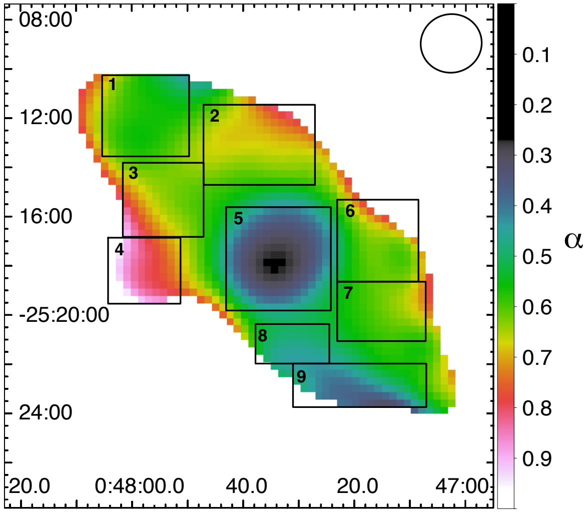
$$\mathbf{t_{diff.} = 3 \times 10^5\ yrs}$$

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

Non-thermal Emission from Which Particles? (Electrons or Protons)

NGC 253: Energy Loss Emission





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

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

$$\mathbf{E_\gamma = 5 \times 10^8\ eV}$$

Gamma-Rays

Radio/Microwave

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

NGC 253: Gamma-Ray Perspective

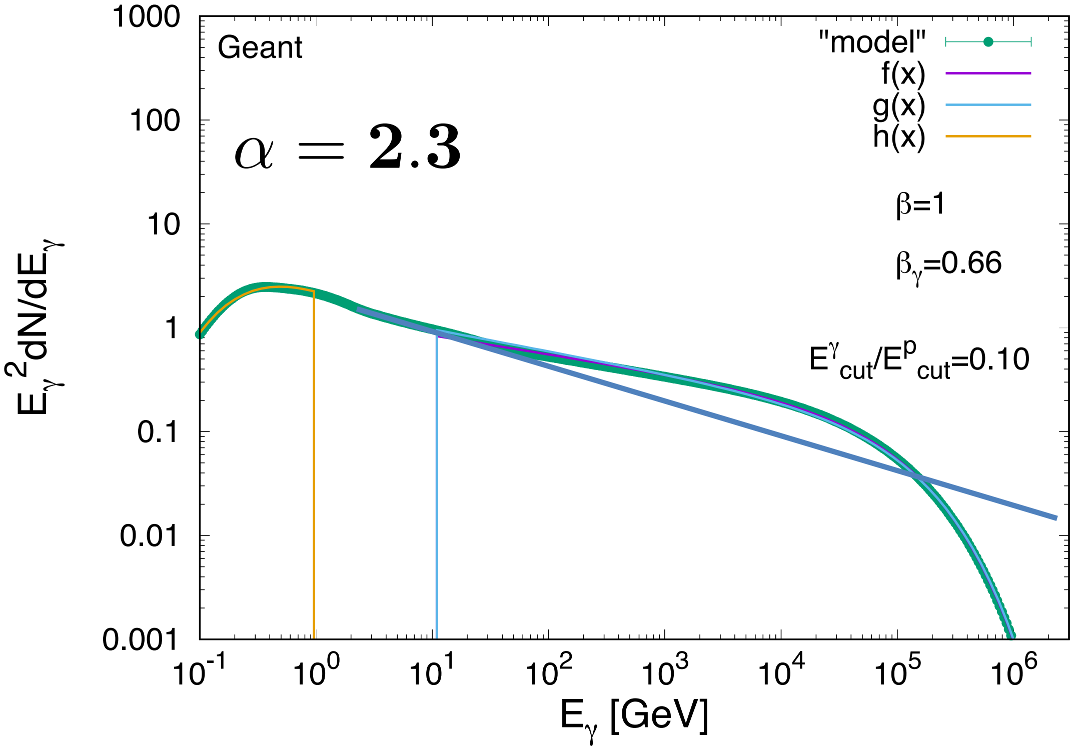
- The gas in a galaxy can act as either a “Thin” or “Thick” target for the CRs

- Thick ($\tau_{\mathbf{esc}} \gg \tau_{\mathbf{loss}}$):
  - All particles lose all their energy before they can leave
  - Gamma spectral index = CR spectral index

- Thin ($\tau_{\mathbf{esc}} \ll \tau_{\mathbf{loss}}$):
  - Fraction of the particles escapes the starburst via advection
  - Higher energy CRs loose energy more efficiently
  - Gamma spectral index ≠ CR spectral index

NGC 253: Hadronic Gamma-Ray Emission

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



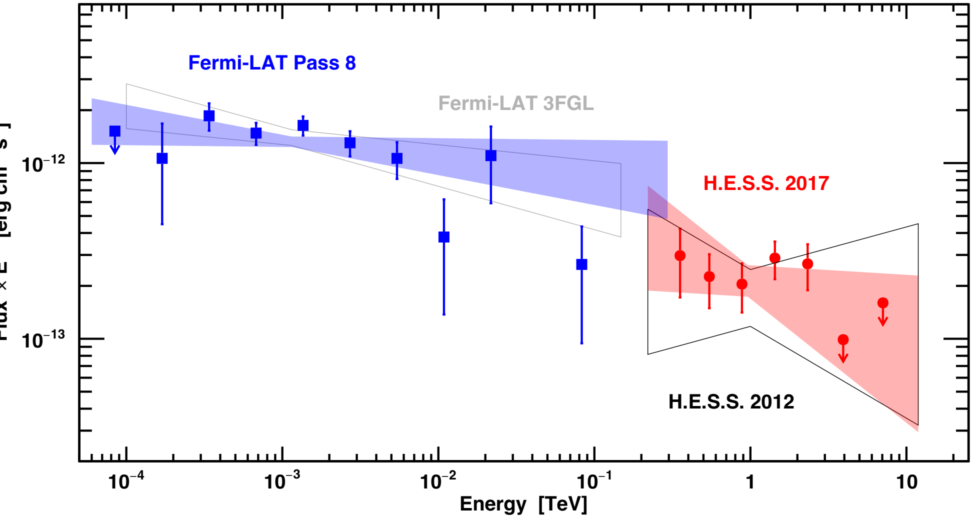
$$J_p(p_p) = \frac{A}{p_p^\alpha} \exp\left[-\left(\frac{p_p}{p_p^{\max}}\right)^\beta\right]$$

Kafexhiu+ Phys.Rev. D90 (2014)

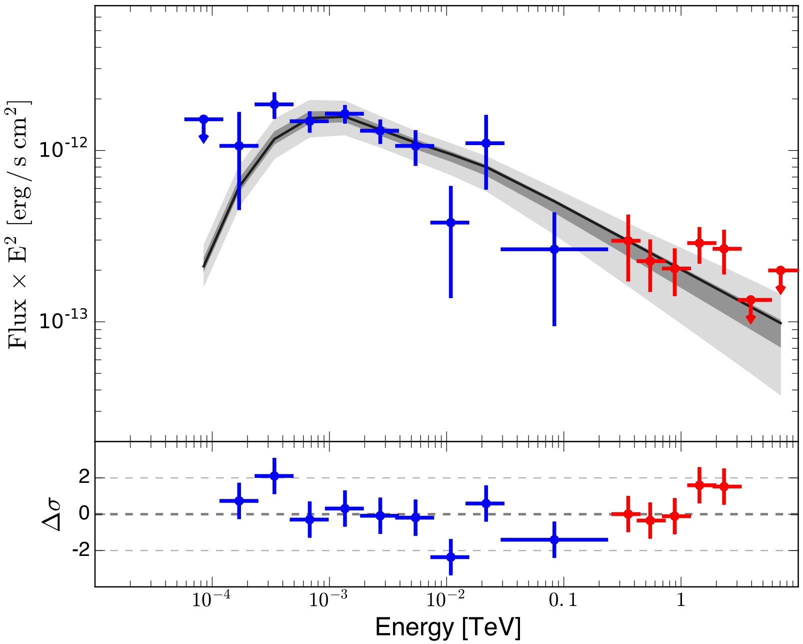
Above threshold, a hardening of the photon spectrum occurs, with the index decreasing by ~0.04 each decade.

NGC 253: Gamma-Ray Perspective

- Index =2.22±0.06 **Thick Target**



- Index =2.46±0.03 **Thin Targe**



NGC 253: Hadronic Colorimetric Fraction Estimation

- Calorimetric fraction estimate
  → How much of the available CR power goes into pion production?

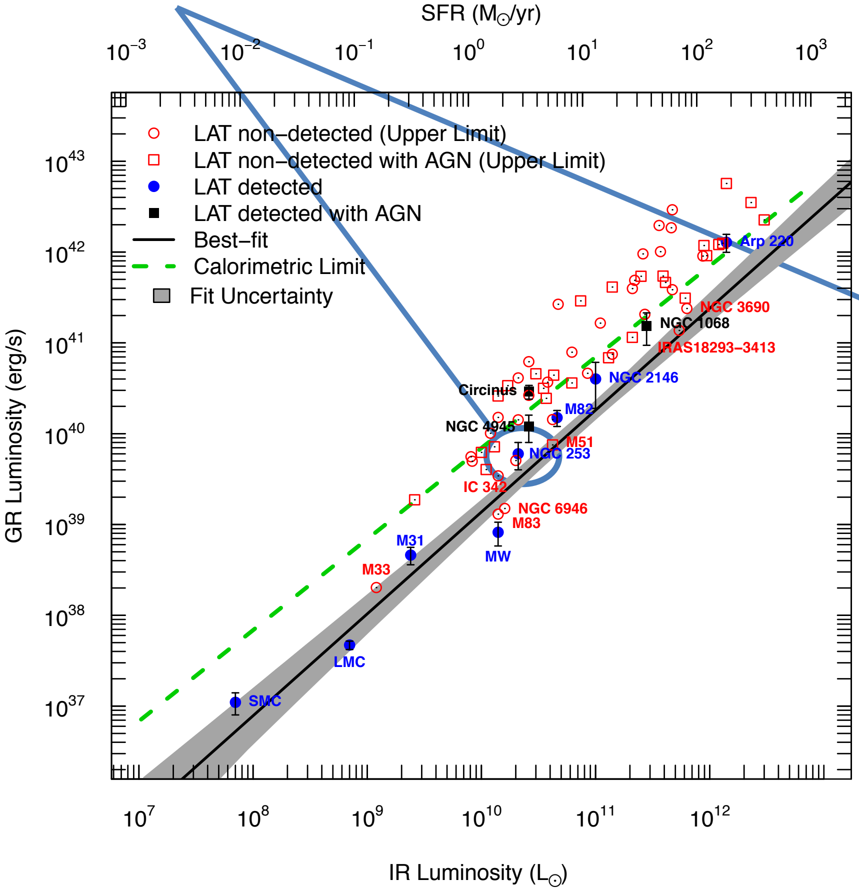
  - Fraction of particles able to do pion production:

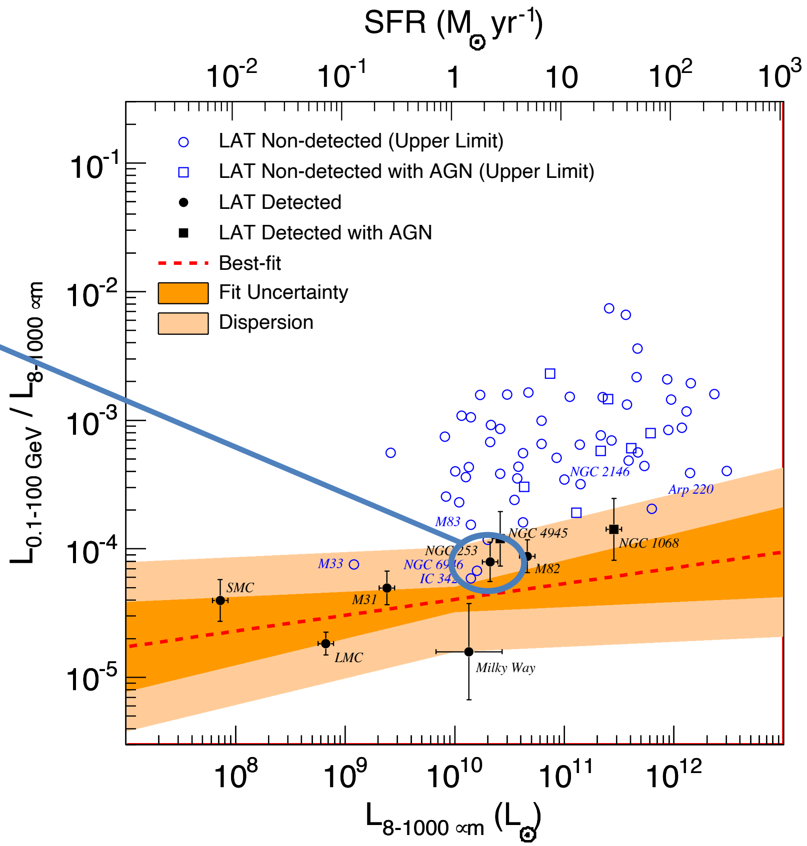
$$\mathbf{f_{cal} = \frac{L_\pi}{L_{CR}(> E_\pi^{th.})} \approx 0.3 \left(\frac{0.7}{f_\pi}\right) \left(\frac{L_\gamma}{10^{40} ergs^{-1}}\right) \left(\frac{2 \times 10^{41} ergs^{-1}}{L_{CR}}\right)}$$

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

Gamma-Ray/Radio/Infrared Correlation

NGC 253



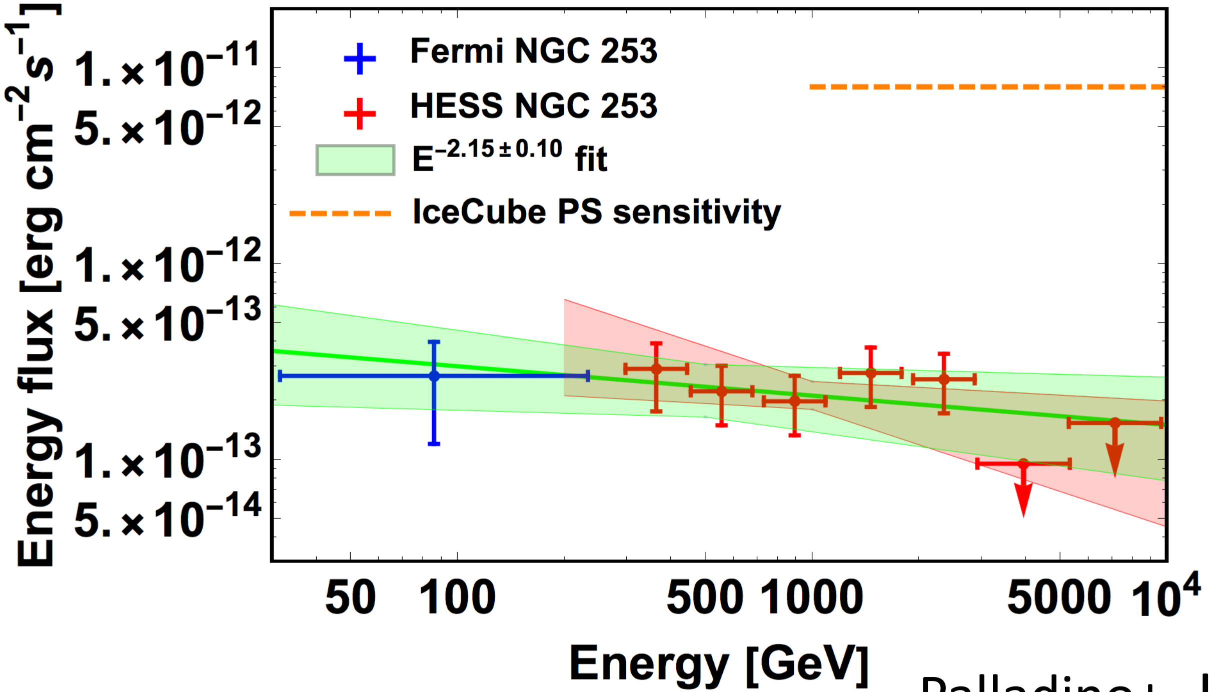


Rojas-Bravo & Miguel Araya, MNRAS, 463 (2016)

Ackermann+, ApJ, 755 (2012)

Other Non-Thermal Particle Energy Loss Signatures

Neutrinos from NGC 253



Palladino+, JCAP 1909 (2019) 004

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

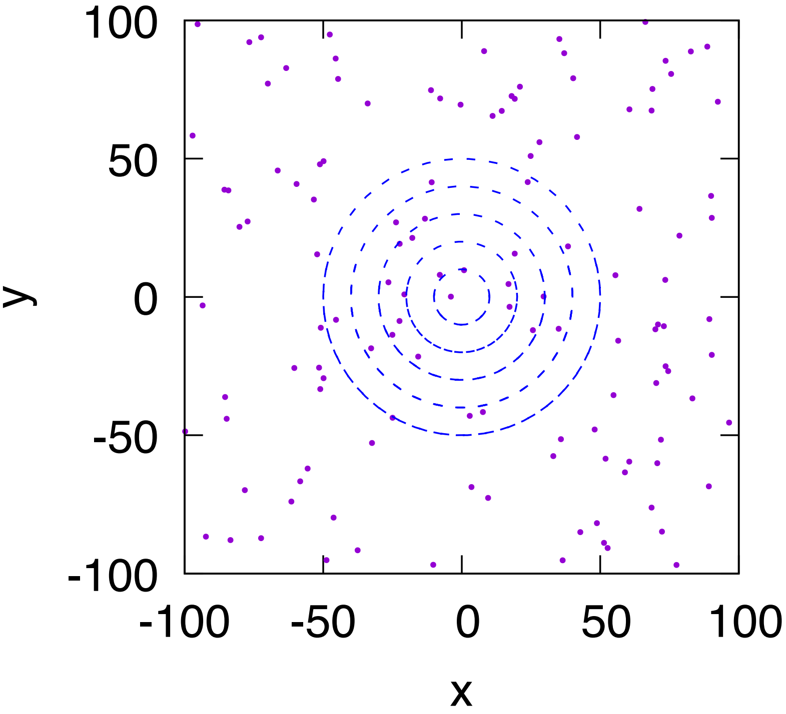
$$\boldsymbol{\rho_0 \approx 10^{-3}\ \mathrm{Mpc}^{-3}}$$

Gruppioni+, MNRAS 432 (2013)

$$\boxed{\boldsymbol{\rho_0 \mathrm{L}_\gamma^{0.1-100} = 2 \times 10^{44}\ \mathrm{erg\ Mpc^{-3}\ yr^{-1}}}}$$

Scaling this Result Up

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

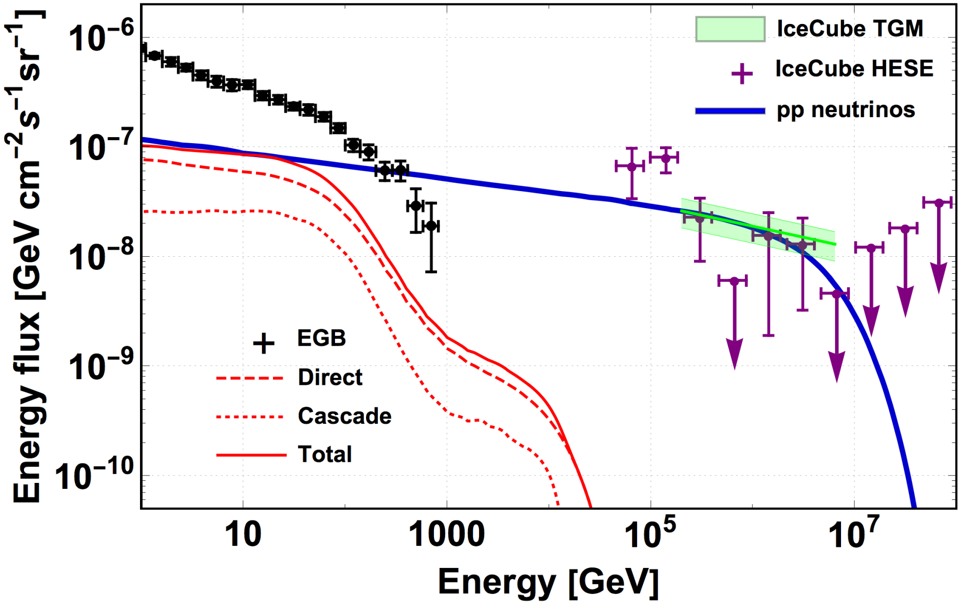


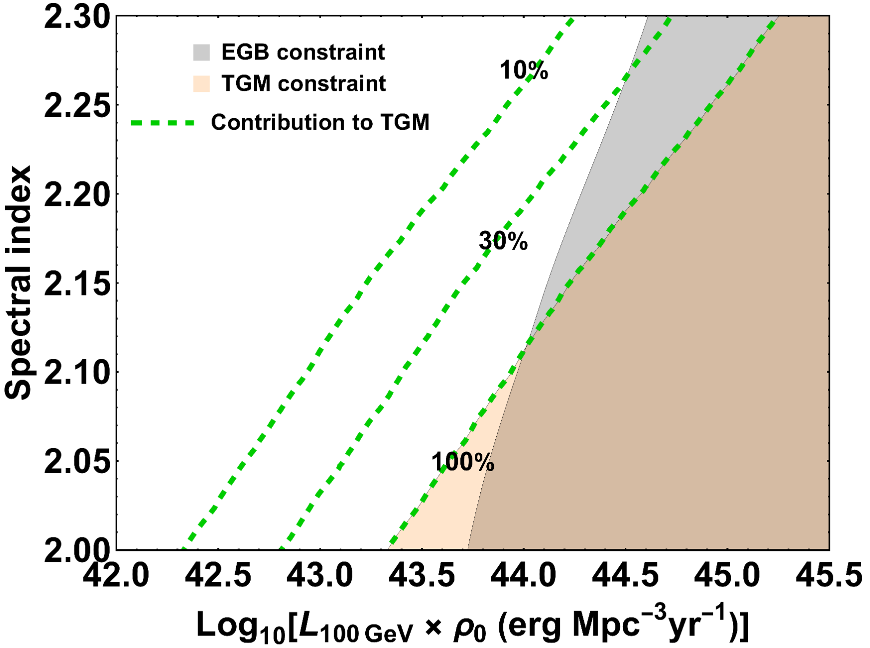
$$\frac{d\Phi_\nu}{dE} \approx \left(\frac{r_{z=1}}{r_0}\right)\Phi_0 \cdot SFR(z=1)$$

$$\approx (4000-5000)\Phi_0$$

Neutrinos from the Ensemble of Starburst Galaxies

Palladino+, JCAP 1909 (2019) 004





		NGC 253	ARP 220	Contribution to		Tension with	
α	$E^\star_{\mathrm{cut}}$	$\rho_0(\alpha)$	$\rho_0(\alpha)$	total EGB	Fermi coll. [41]	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

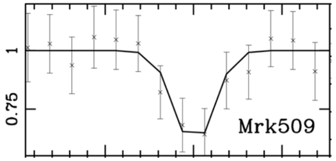
DESY.

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

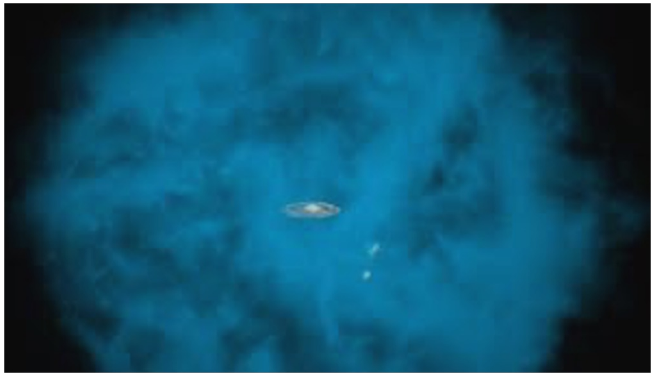
Is Emission from Even Futher Out in the Galactic Halo Expected?

Large Thermal Pressure in the Galactic Halo

X-ray observations of bright AGN indicate the presence of a hot local absorber.

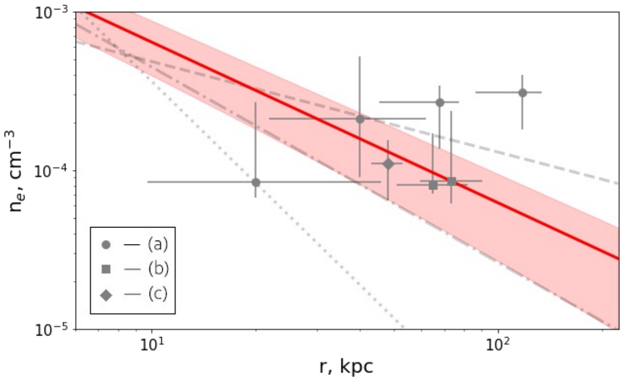


Gupta ApJ, 756 (2012)



More recently, the ram pressure stripping of satellite galaxies + emission from the hot absorber have been collectively used to probe the halo gas density.

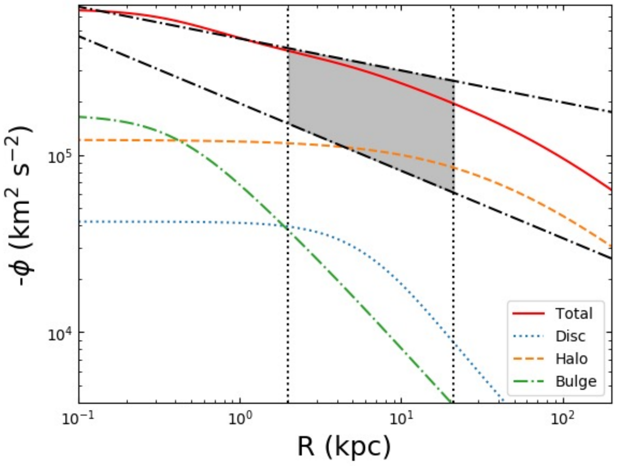
Faerman ApJ 835 (2017), Martynenko MNRAS, 511 (2022)

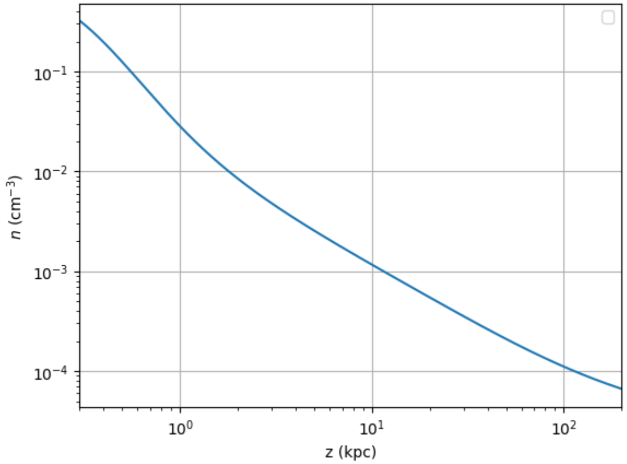


Hydrostatic Equilibrium for a Galaxy

These results are consistent with expectations if the halo gas is in hydrostatic equilibrium

Faerman ApJ 835 (2017),
Tourmente 2207.09189, (2022)

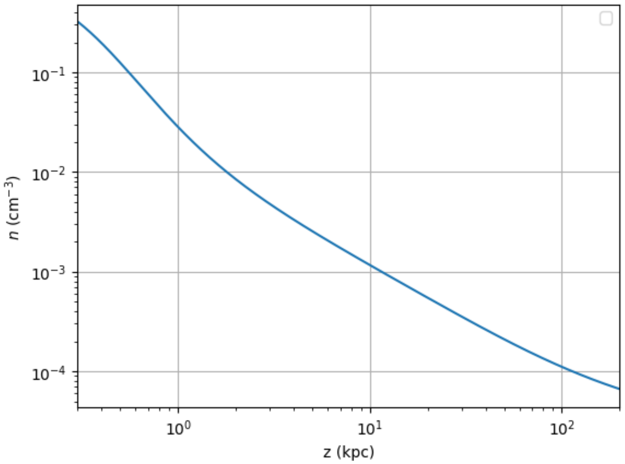




$$\boxed{\frac{\partial \rho \mathbf{v}}{\partial \mathbf{t}} + \nabla \cdot \mathbf{P} = \rho \mathbf{g}}$$

$$\boxed{\rho \frac{\partial \mathbf{v}}{\partial \mathbf{t}} + \rho(\mathbf{v} \cdot \nabla)\mathbf{v} = -\nabla \mathbf{p} + \rho \mathbf{g}} \quad \Longrightarrow \quad \boxed{\rho = \rho_{\mathbf{0}} \mathbf{e}^{-\phi/\mathbf{kT}}}$$

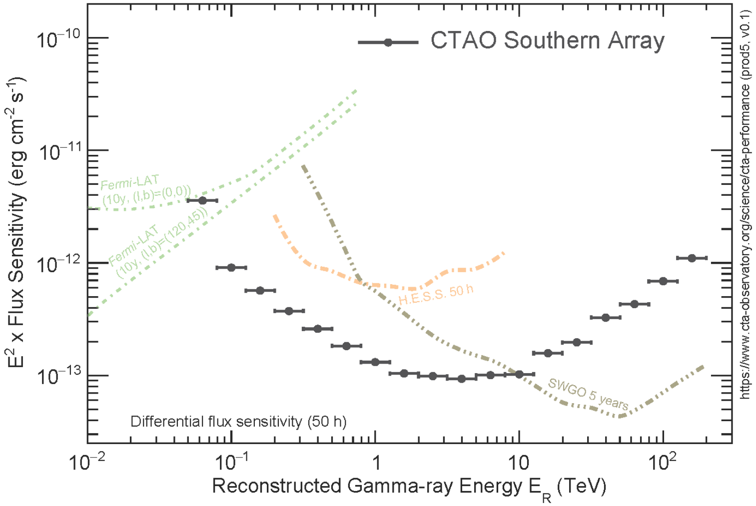
Gamma-Rays from the Galactic Halo?



Only for cosmic rays within 10 kpc from the Galaxy can full calorimetry within a Hubble time, t_H, be achieved

$$\boxed{\mathbf{t_{pp} \approx 2 \times 10^{10} \left(\frac{2 \times 10^{-3}\ cm^{-3}}{n_p} \right)}\ \mathrm{yrs}}$$

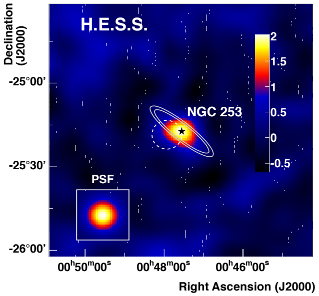
Could there be further emission expected for nearby galaxies that has not yet been observed?

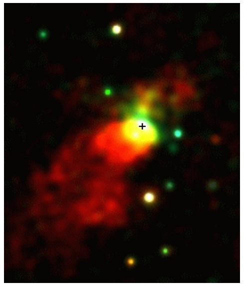


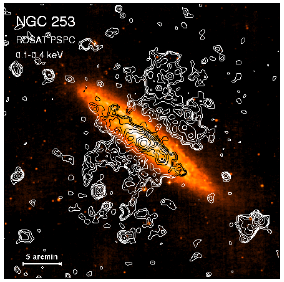
DESY.

An Understanding of the Global Picture

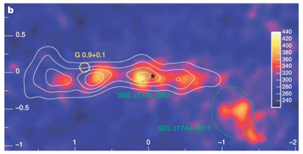
NGC 253

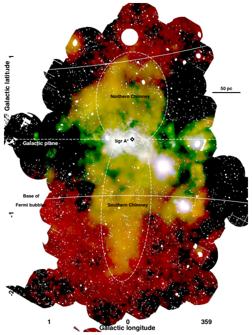


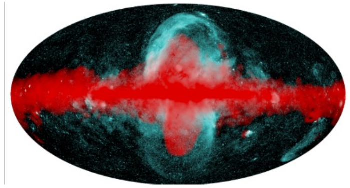


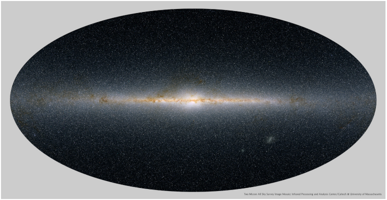


Milky Way



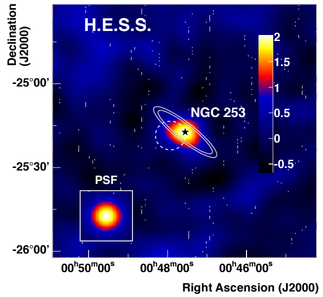


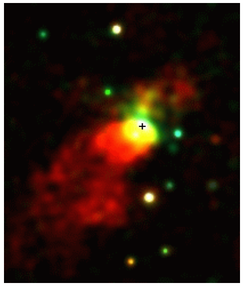


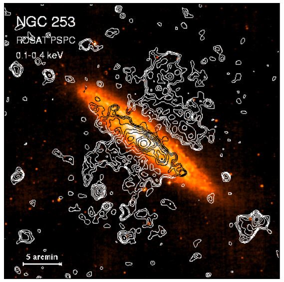


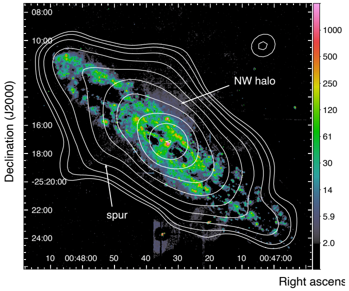
For both NGC 253 and the Milky Way at least, cosmic rays in the Central Molecular Zone region appear to be advected out in a centrally driven outflow

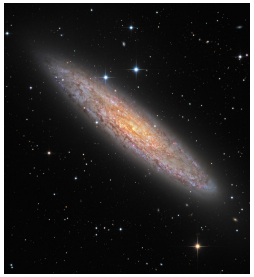
An Understanding of the Global SED



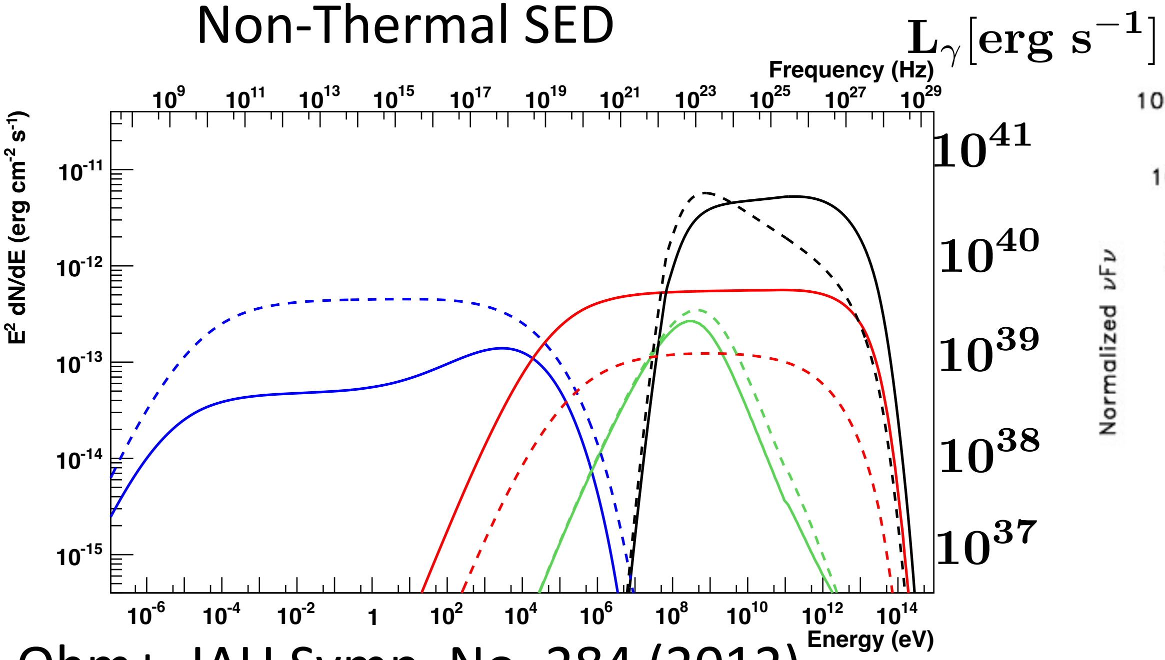




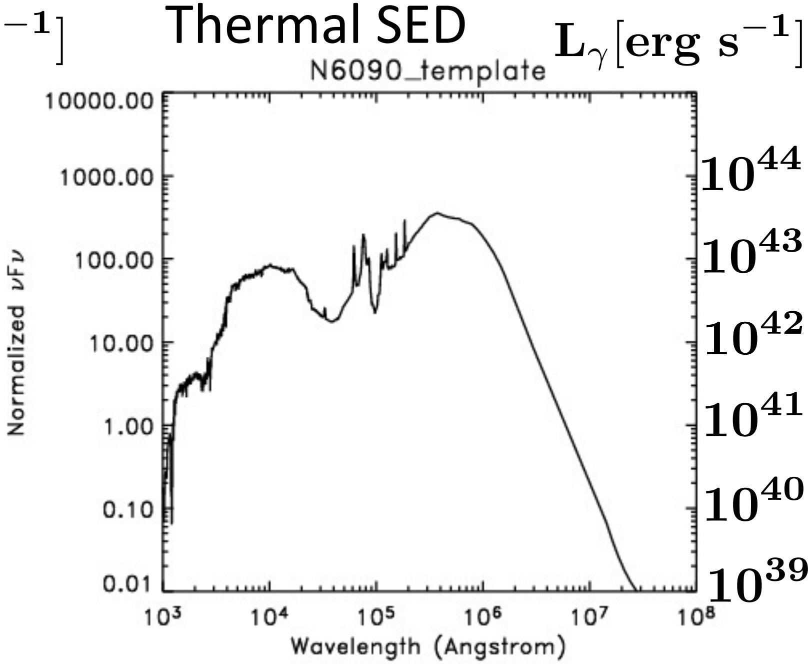




Non-Thermal SED



Thermal SED



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

Summary on Cosmic Rays in Galaxies

- The star forming regions of galaxies are particularly dusty thanks to enhanced activity of massive stars, giving rise to larger IR emission
- Their gamma-ray emission is believed hadronic (pp) in origin, emanating (in part at least) from the galactic center region, with the Galactic nucleus emission region being presently unresolved.
- Their gamma-ray emission appears to grow faster than linearly with their IR emission (both beam and target increase with luminosity).
- Cosmic rays accelerated in the Galactic nuclear region appear to be advected out of the Galaxy in a centrally driven outflow
- Although individually these are weak sources, collectively they could account for a significant fraction of the residual diffuse gamma-ray and neutrino backgrounds