Are starburst galaxies proton calorimeters?

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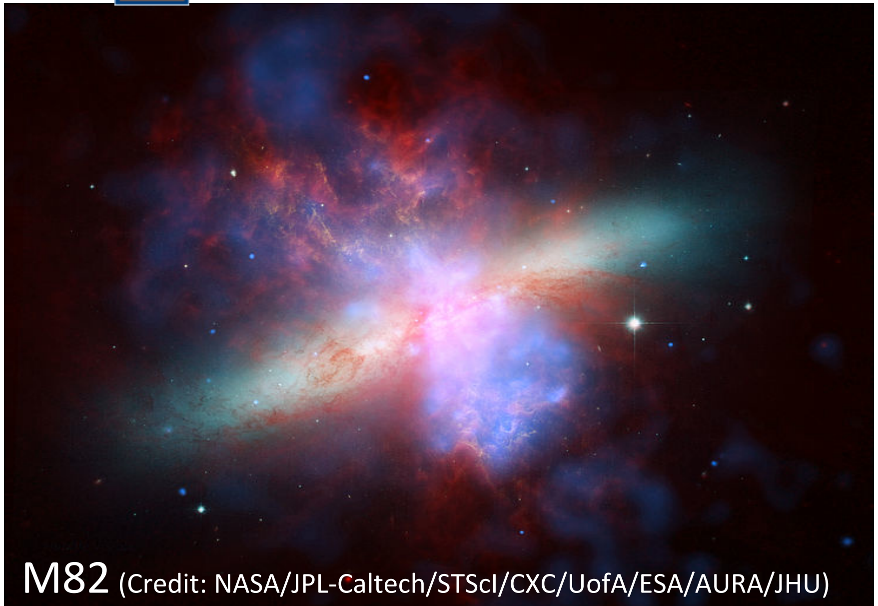


M82 (Credit: NASA/JPL-Caltech/STScI/CXC/UofA/ESA/AURA/JHU)

See Todd Thompson’s talk

Star Form: Ordinary to Extreme

Normal Star-Forming Galaxies:

- MW-like, SFR ~ 1 $M_\odot$/yr
- CR most escape
- Common in universe today

Starburst Galaxies:

- High SFR ~ few to few tens $M_\odot$/yr
- High density of gas
- CR most “die” in collision (Lacki et al., 2011)
- Common in early universe

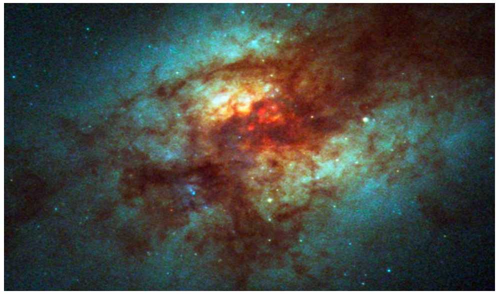
Ultraluminous Infrared Galaxies (ULIRG):

(See Tova Yoast-Hull’s talk)

- “Very extreme starbursts”
- Even higher SFR ~ $10^{2\text{-}3}$ $M_\odot$/yr

The Milky Way (Credit: ESO/S. Brunier)

M82 (Credit: NASA, ESA and the Hubble Heritage Team STScI/AURA)



Arp220 (credit: NASA, ESA, and C. Wilson (McMaster University, Hamilton, Ontario, Canada))

Cosmic Rays: Lesson From MW Gamma Rays

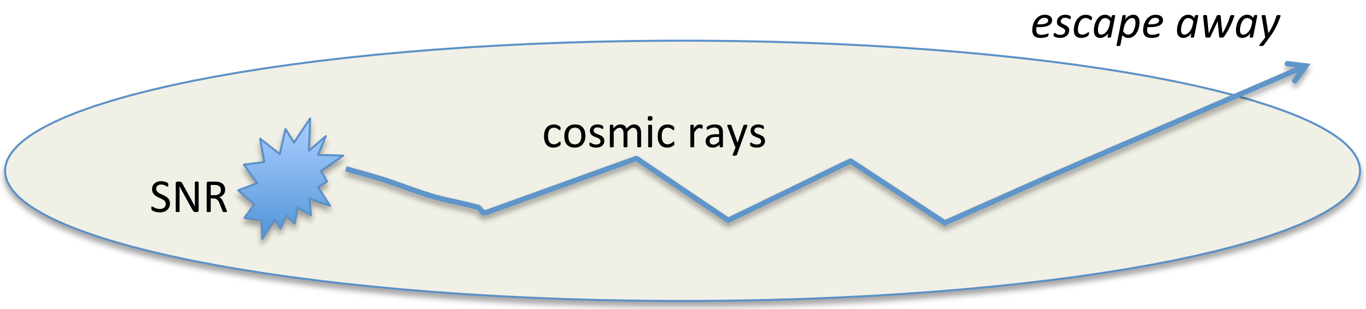
- Dominant gamma-ray process: hadronic Interactions between CRs and ISM:

$$p_{CR} + p_{ISM} \rightarrow \pi^0 \rightarrow \gamma\gamma$$

- Resultant pionic gamma ray spectrum:
  - "pion bump" feature expected at $E_\gamma = m_\pi / 2$ (Stecker 1971)
- CR Accelerators: (Baade & Zwicky 1934; Ginzburg & Syrovatskii 1964)
  - Supernovae
  - Pion decay feature of SNR IC443 & W44 gamma spectra seen by Fermi (Ackermann et al 2013)

Global model

MW: escape dominant, “thin-target”

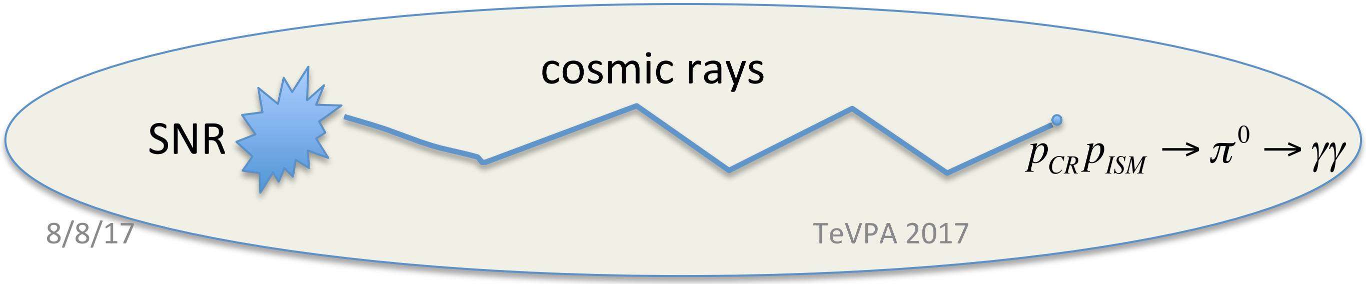


Starbursts: collision dominant, “thick-target”

- Injected proton spectrum is a power law: $q_p \propto p^{-s}$
- CR acceleration depends on SN:

$$L_{CR} = E_{SN}\varepsilon_{SN}R_{SN} = \varepsilon_{CR}R_{SN} = V\int_{T_{\min}}^{\infty} T q_p \, dp \rightarrow q_p \propto \varepsilon_{CR}R_{SN}p^{-s}$$

- No escape cosmic rays
- Loss include elastic, inelastic scattering (pionic process), ionization
- Independent of gas density
- Gamma rays only depends on CR acceleration: ε_{CR} & s



Test for Model's key features

For the resultant gamma spectra, True or not?

? Flux value $F_\gamma \propto \varepsilon_{CR}$;

? shape depend on injected CR index s only;

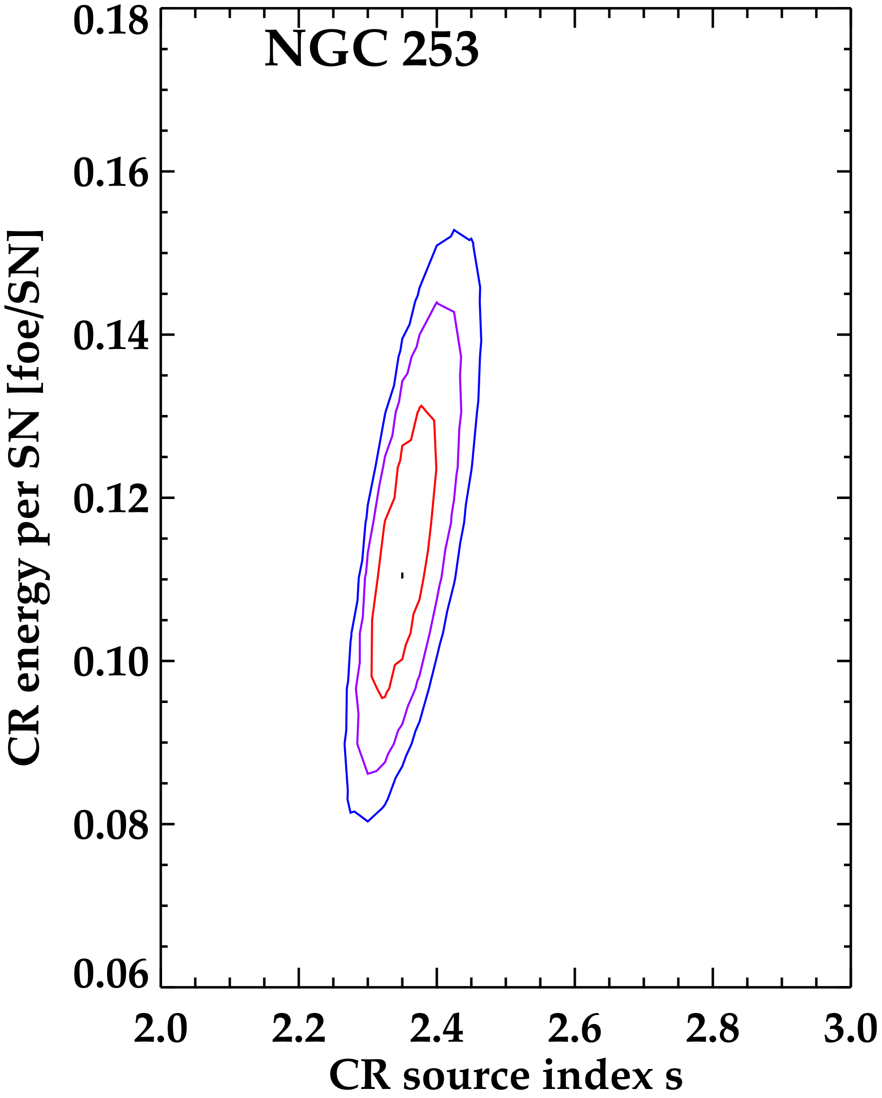
? TeV gamma-ray spectra index = injected CR index s;

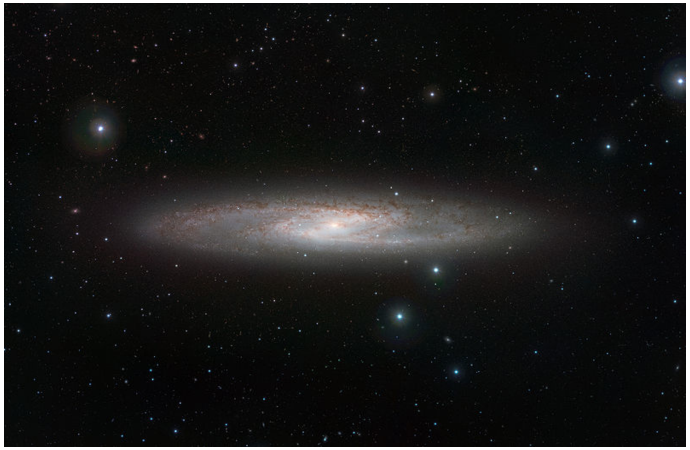
? "Pion-bump" peak at $E_\gamma = m_\pi / 2$ for Φ_γ ;

? Best-fit ε_{CR} & s agree with observed SN-accelerated CR properties?

arXiv:1612.07290

Individual Starburst





NGC253(Credit: ESO/J. Emerson/VISTA)

$$s = 2.350 \pm 0.037$$

$$\varepsilon_{cr} = 0.116 \pm 0.013\ foe$$

$$D = 2.5\mathrm{Mpc}$$

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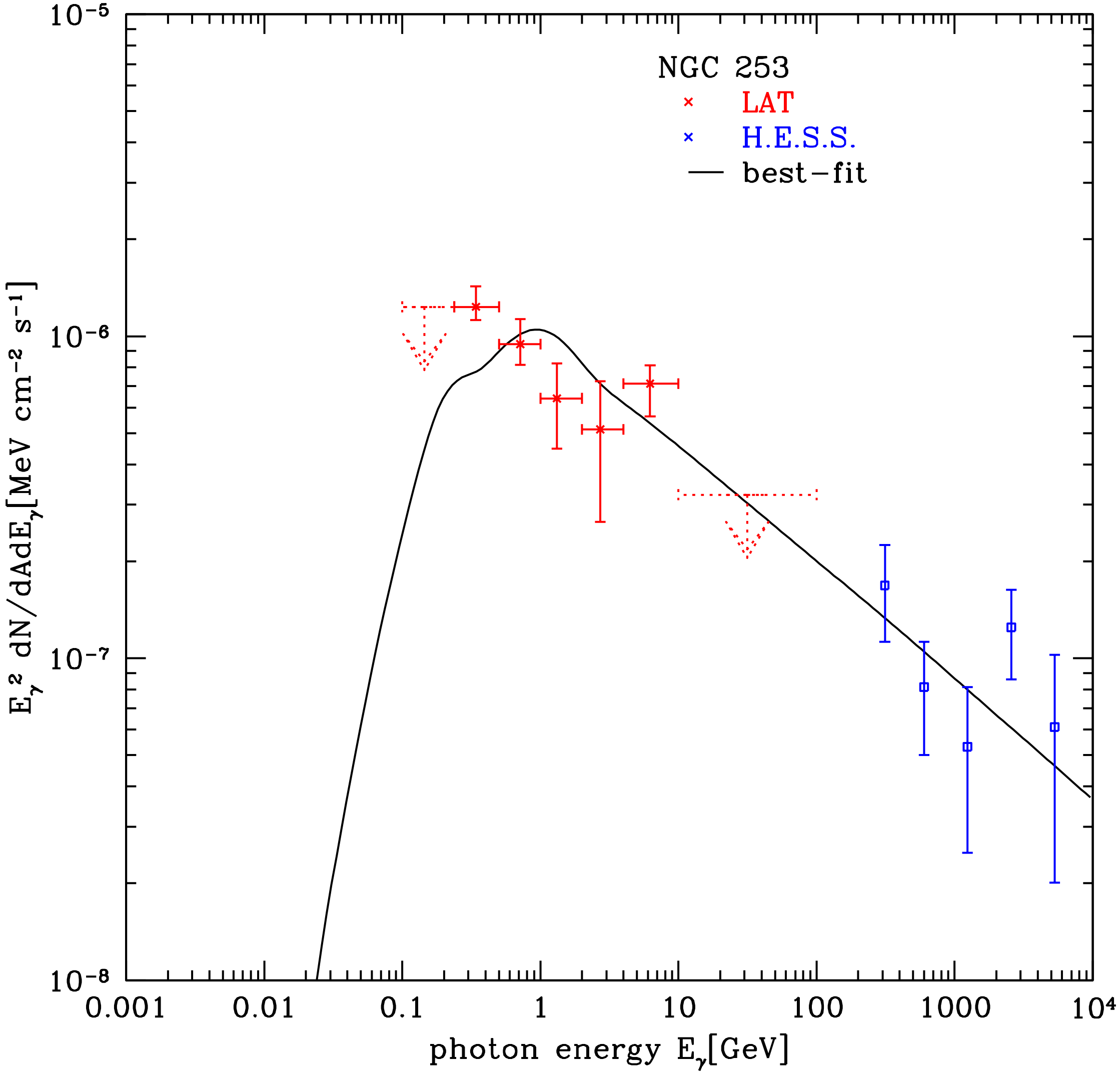

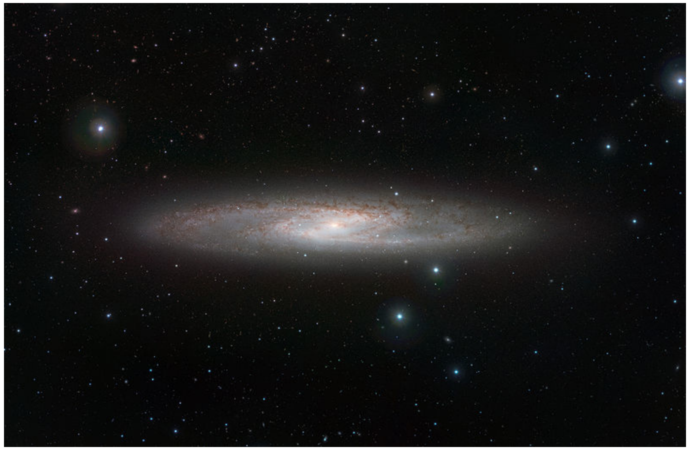

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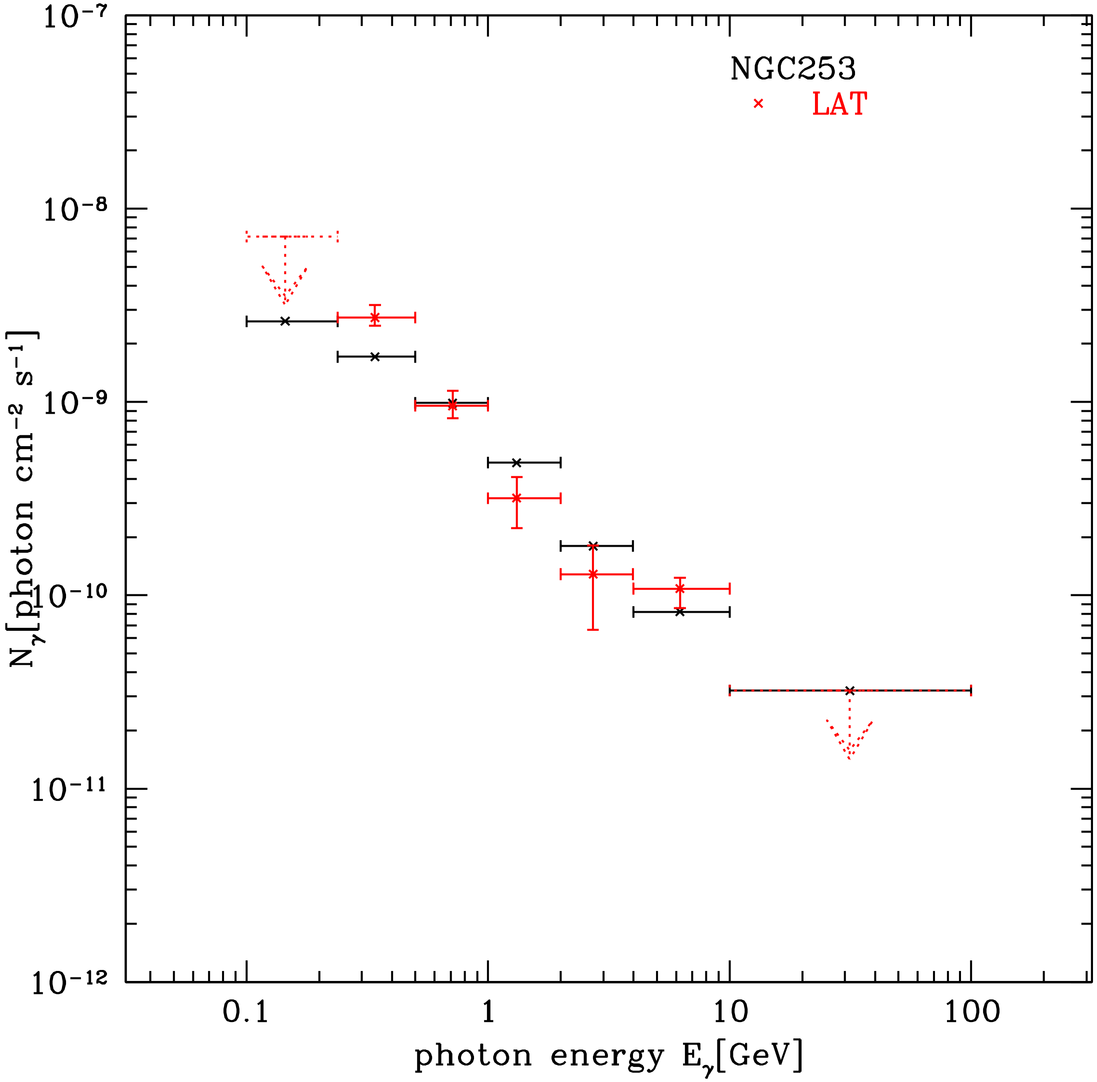

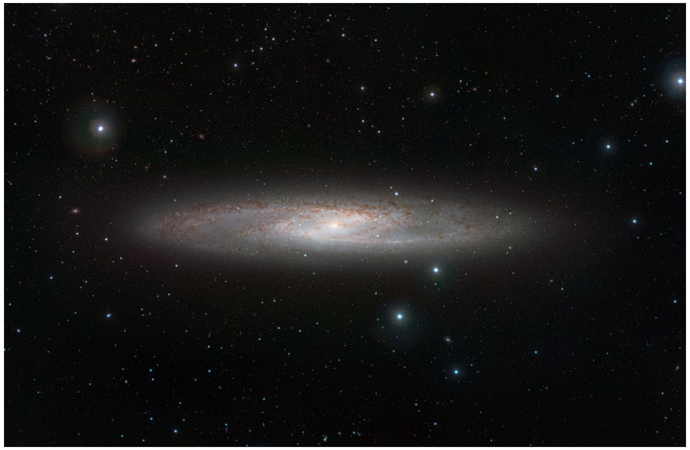

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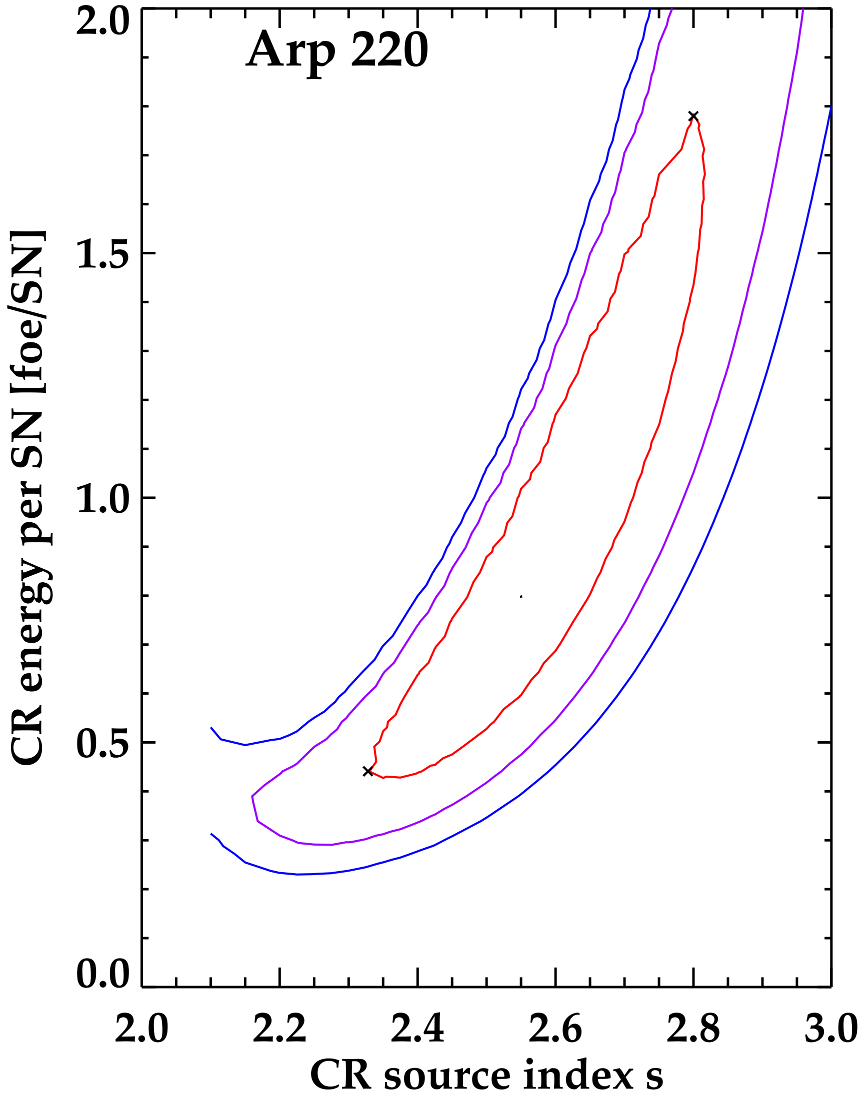

Arp220 (credit: NASA, ESA, and C. Wilson (McMaster University, Hamilton, Ontario, Canada))

$$s = 2.550 \pm 0.257$$

$$\varepsilon_{cr} = 0.808(> 0.404)\, foe$$

$$D = 77\,\mathrm{Mpc}$$

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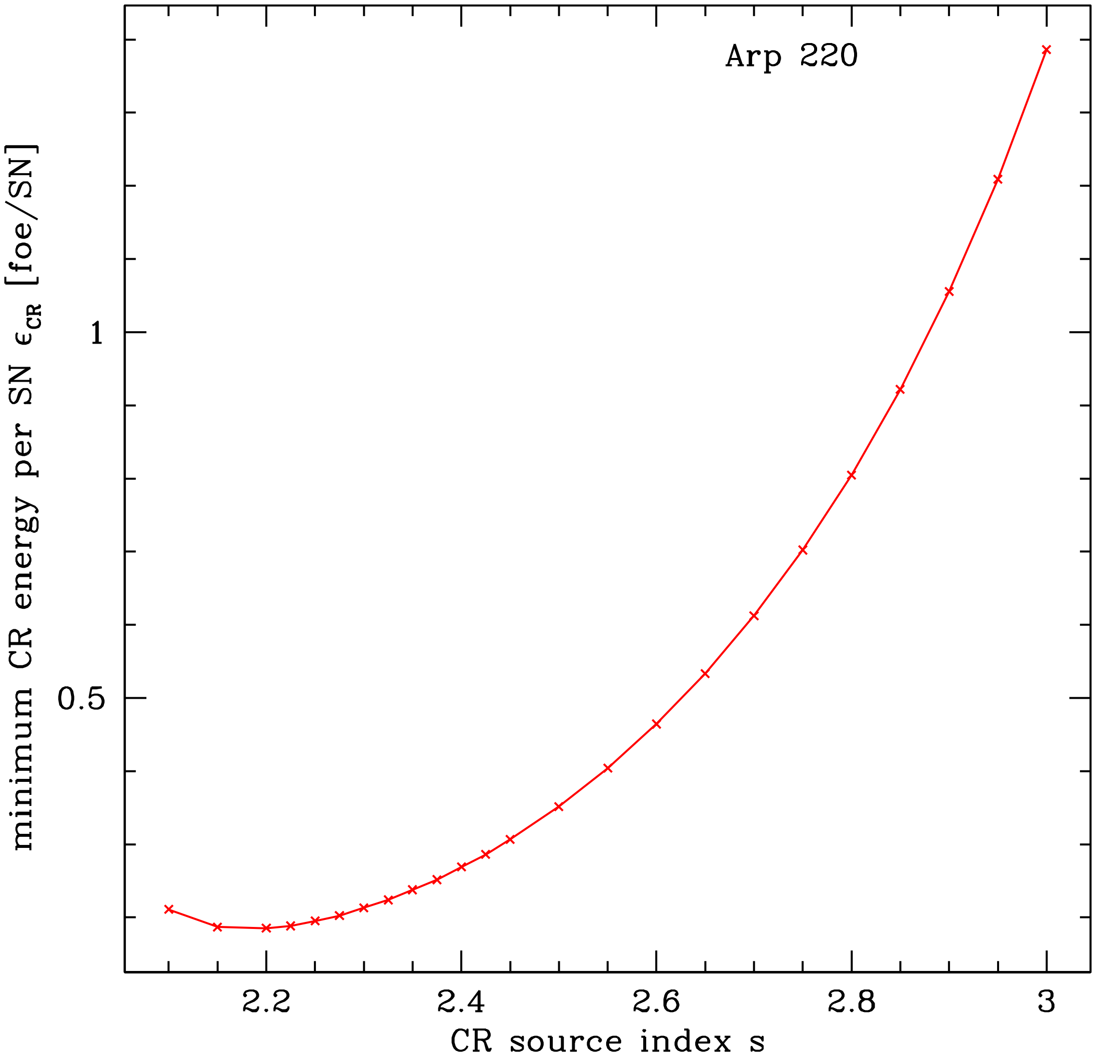
Individual Starburst



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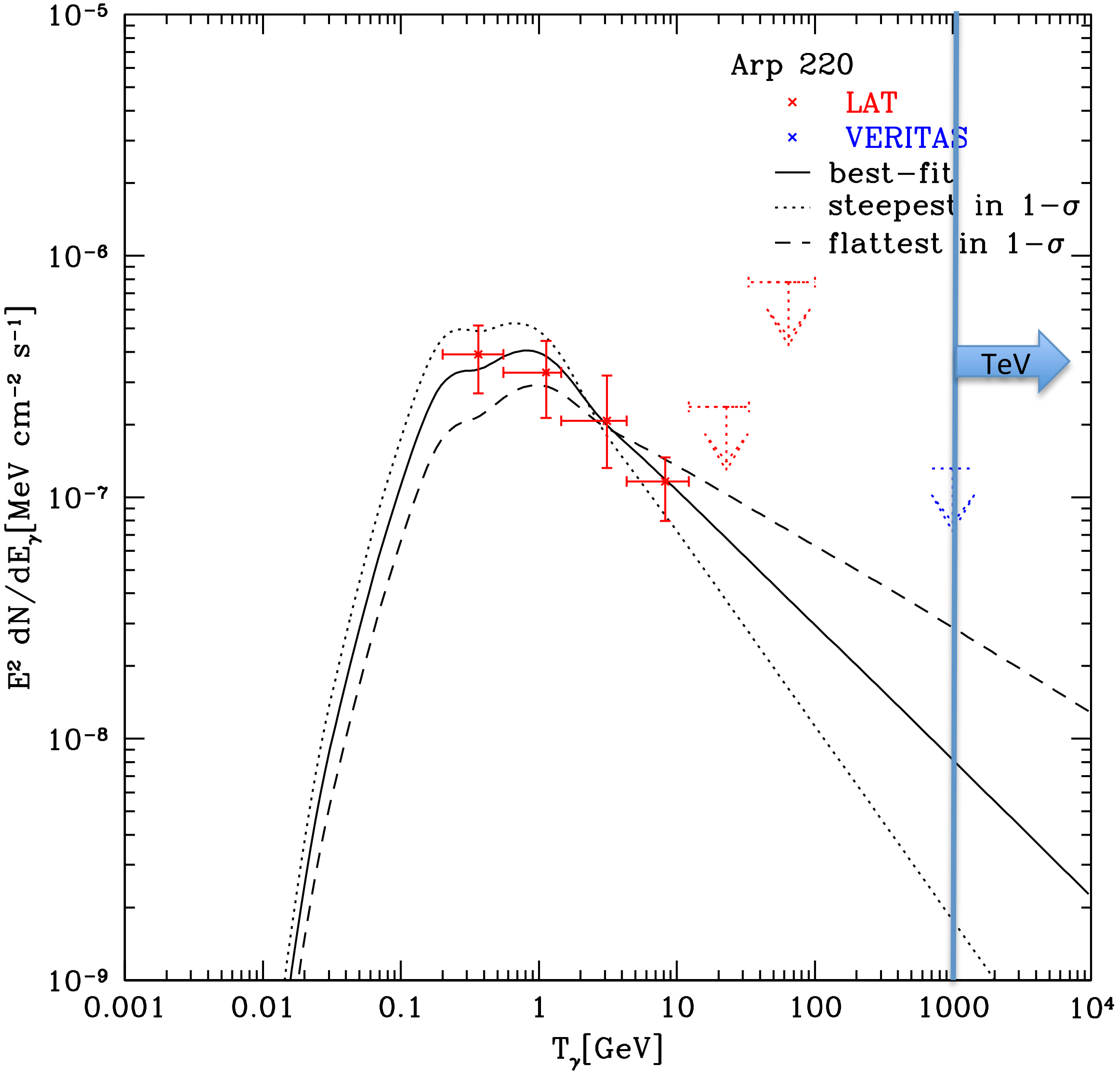

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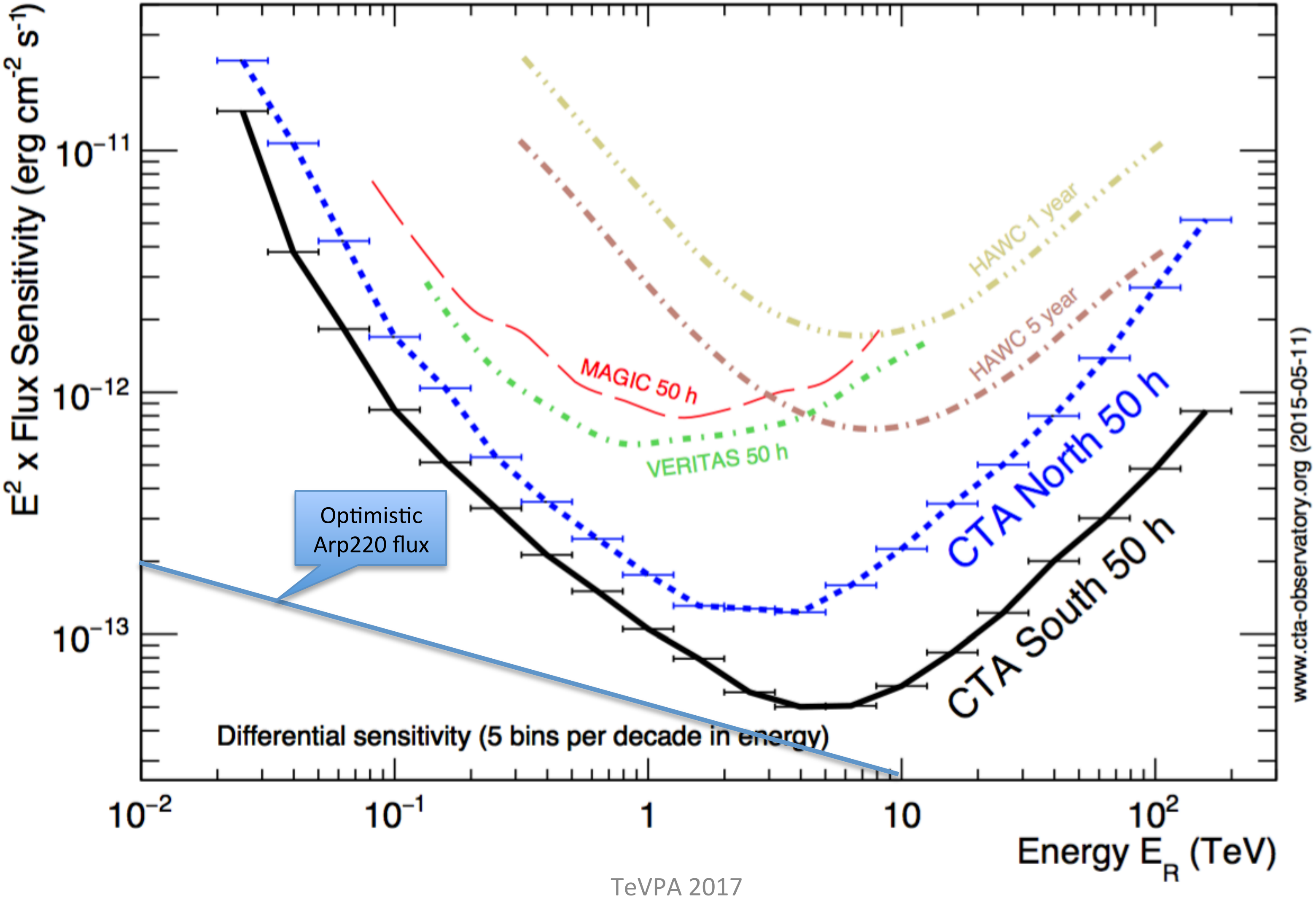
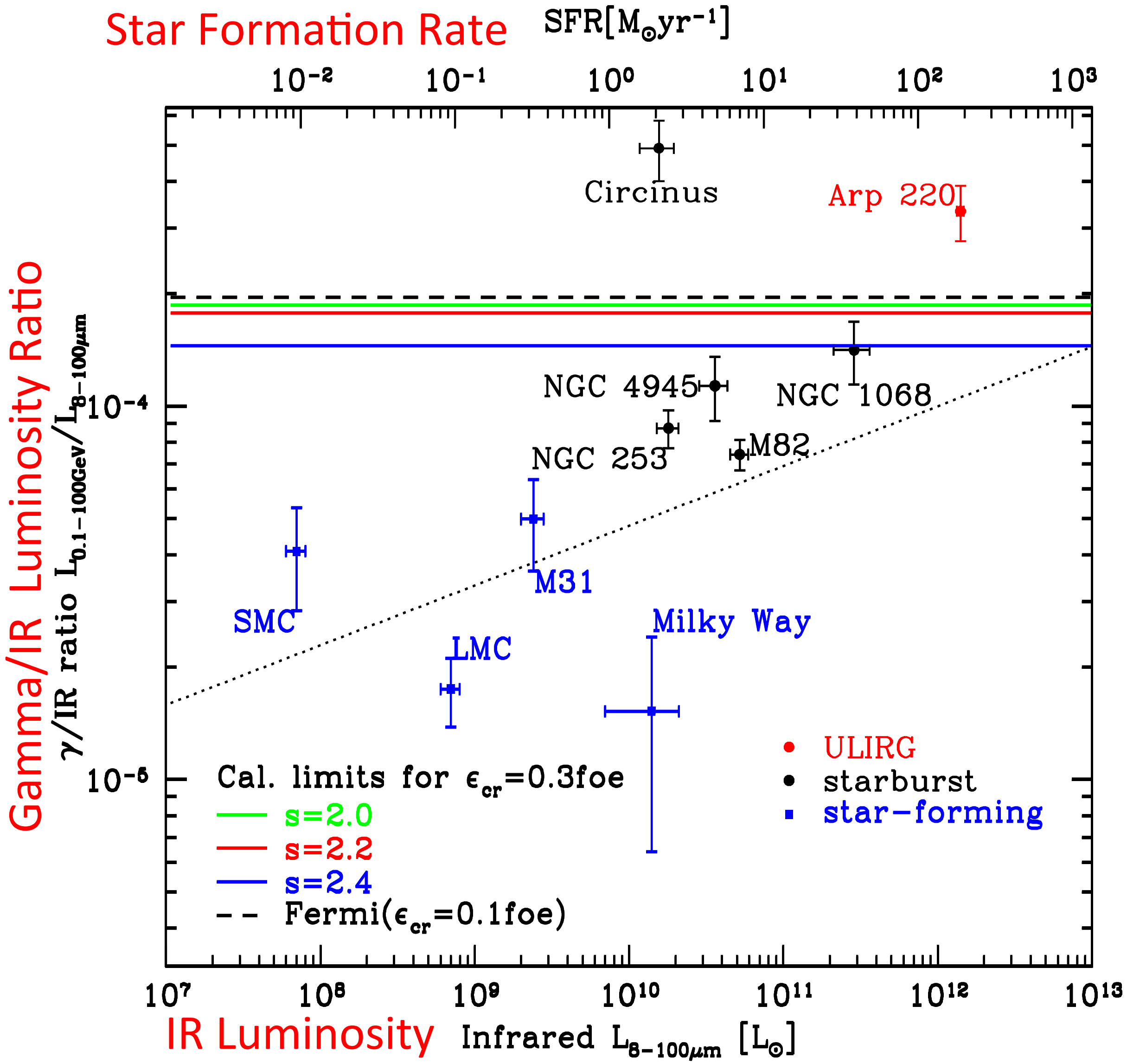
TeV telescope sensitivity



Optimistic Arp220 flux

arXiv:1612.07290

Calorimetric Limit



$$\begin{aligned}\varepsilon_{CR} &= \varepsilon_{SN} E_{SN} \\ &= 3\times 10^{50}\, erg \\ &= 0.3\, foe\end{aligned}$$

Discussion

- M82, NGC253, NGC1068 and NGC 4945:

  proton calorimetry holds;

  much higher calorimetric efficiencies
- The Circinus galaxy:

  the calorimetric relation fails;

  GeV excess: existence of other gamma-ray sources (like AGN).
- ULIRG Arp220

  not a proton calorimeter like Circinus;

  or it’s a full calorimeter, with more efficient supernovae acceleration or higher supernova rates in ULIRGs

Summary

Test Results:

? Proton calorimetry Yes! For most starbursts

? $\varepsilon_{CR} \approx \varepsilon_{CR}^{MW}$ Yes!

? $s \approx s^{MW}$ Yes!

? “pion bump” Incomplete → MeV data needed for all starbursts!

? TeV spectra slope? Incomplete → TeV data needed for NGC 4945, NGC 1068, Circinus, Arp220 !

- Backup slides

Model Assumptions & Equations

- Injected proton spectrum is a power law:

$$q_p = \frac{dq}{dp} = q_0 p^{-s}$$

- Cosmic rays accelerated by supernovae (energy conservation):

$$L_{CR} = E_{SN}\varepsilon_{SN}R_{SN} = \varepsilon_{CR}R_{SN}$$

$$= V\int_{T_{\min}}^{\infty} T\frac{dq}{dp}dp = Vq_0\int_{T_{\min}}^{\infty} T \bullet p^{-s}\,dp = Vq_0E_0I_0(T_{\min})$$

$$\rightarrow q_p \propto \varepsilon_{CR}R_{SN}p^{-s}$$

- One-zone model: $n_{ISM} = \text{constant}$
- Pionic process dominates gamma-ray production mechanisms:

$$\text{crosssection } \sigma = \sigma_{pp\rightarrow\pi^0}$$

Model Assumptions & Equations

- Energy loss include hardronic elastic scattering, inelastic scattering and EM energy loss (ionization):

$$b(E_p) = \left| -dE/dt \right| = b_{elastic} + b_{inelastic} + b_{ionic}$$

- No escape cosmic rays (number conservation):

$$\tau_{escape} = \infty$$

⇨ Propagation equation for CR:

$$\partial_t N_E = \partial_E \left(b N_E \right) - \frac{1}{\tau_E} N_E + q_p \xrightarrow[\text{steady state}]{\text{thick target limit}} q_p = -\partial_E \left(b N_E \right)$$

$$\xrightarrow[\text{proton flux}]{\textit{accelerated}} \Phi_p \left(E_p \right) = v_p N_E = \frac{v_p}{b(E_p)} \int_{E_p}^{\infty} dE q_p(E) \propto \varepsilon_{CR} R_{SN} q(> E_p, s)$$

Model Equations: gamma-ray emission

$$q_\pi(T_\pi)\left[pions/(cm^3\cdot s\cdot GeV)\right]=n_H\int_{T_p^{\min}(T_\pi)}^{\infty} dT_p\cdot\phi_p(T_p)\cdot\frac{d\sigma(T_\pi,T_p)}{dT_\pi}$$

$$q_\gamma(\varepsilon_\gamma)\left[photons/(cm^3\cdot s\cdot GeV)\right]=2\int_{\varepsilon_\gamma+\left(m_\pi^2/4\varepsilon_\gamma\right)}^{\infty} dE_\pi\cdot\frac{q_\pi(E_\pi)}{\left(E_\pi^2-m_\pi^2\right)^{1/2}}$$

(C.D.Dermer 1986)

$$q_\gamma \propto \varepsilon_{CR}R_{SN}I(s)$$

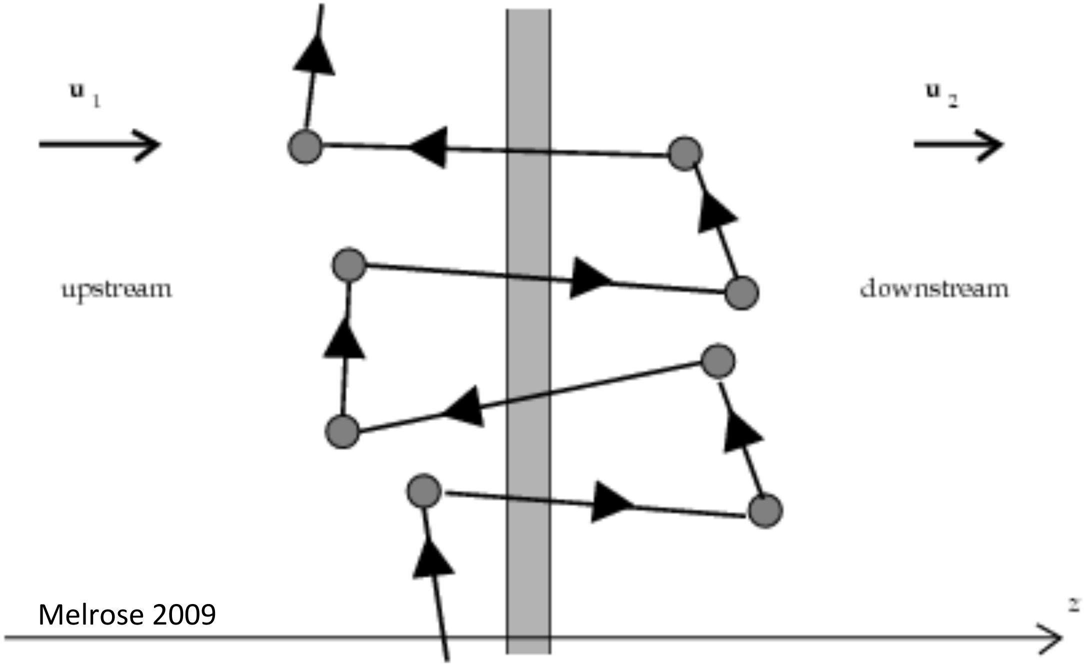
$$\Phi_\gamma=\frac{q_\gamma V}{4\pi d^2}\propto \varepsilon_{CR}R_{SN}I(s)$$

For certain starburst galaxy, only 2 free parameters in the model:

- CR source spectrum index s
- CR acceleration energy per supernova ε_{CR}

Diffusive Shock Acceleration

- Basic idea: 1st-order Fermi mechanism (Fermi 1949)



Melrose 2009

→ resulting CR spectrum accelerated by SN:

$$dN_{CR}/dp \propto p^{-s},$$

$$s = 2 + \frac{4}{M^2 - 1} \approx 2 \text{ for strong shock } M \gg 1$$

“Pion-bump”

- For the pionic reaction:

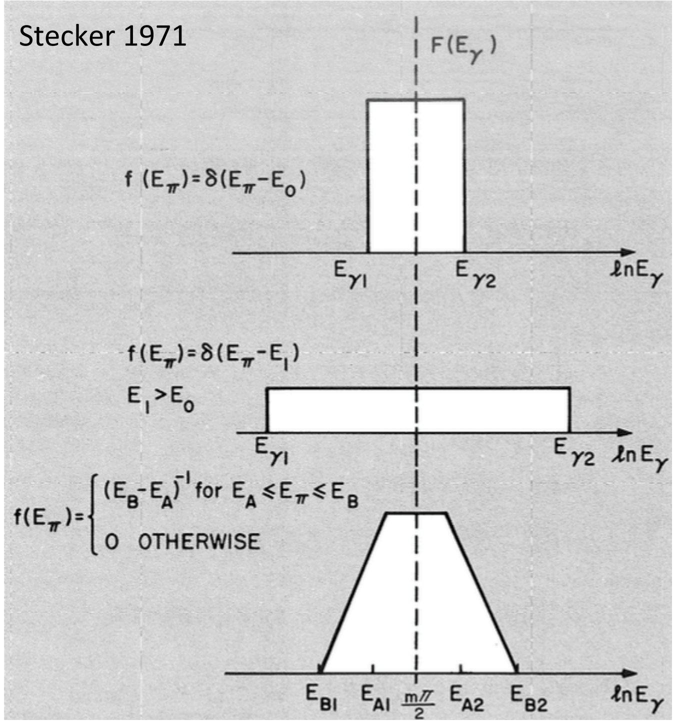
$$p_{CR} + p_{ISM} \rightarrow \pi^0 \rightarrow \gamma\gamma$$

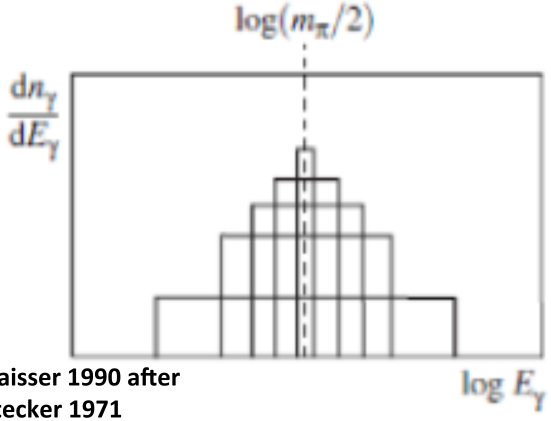
- the gamma-ray distribution function

$$F_\gamma = dN_\gamma / dE_\gamma$$

is a maximum at $E_\gamma = m_\pi / 2$ (Stecker 1971), i.e., when two photons decayed from neutral pion travel oppositely to each other with the same energy.

→ the pionic gamma-ray spectrum has a “pion bump” feature.


Stecker 1971



Gaisser 1990 after Stecker 1971

High-energy behavior

- At high energy,

$$b(E_p) \propto E_p$$

$$\Rightarrow \Phi_p = \frac{vq_p(>E_p)}{b(E_p)} \propto E_p^{-s}$$

$$\frac{d\sigma(T_p, T_\pi)}{dT_\pi} \propto \frac{1}{T_p} \; for \text{ high } T_\pi$$

$$\Rightarrow \Phi_\pi \propto E_\pi^{-s} \Rightarrow \Phi_\gamma \propto E_\gamma^{-s}$$

Therefore, at high energy, resultant gamma-spectrum will be a power law with the same spectral index s as the injected proton spectrum.