Starburst Galaxies: A View into the Workings of Cosmic Ray Factories

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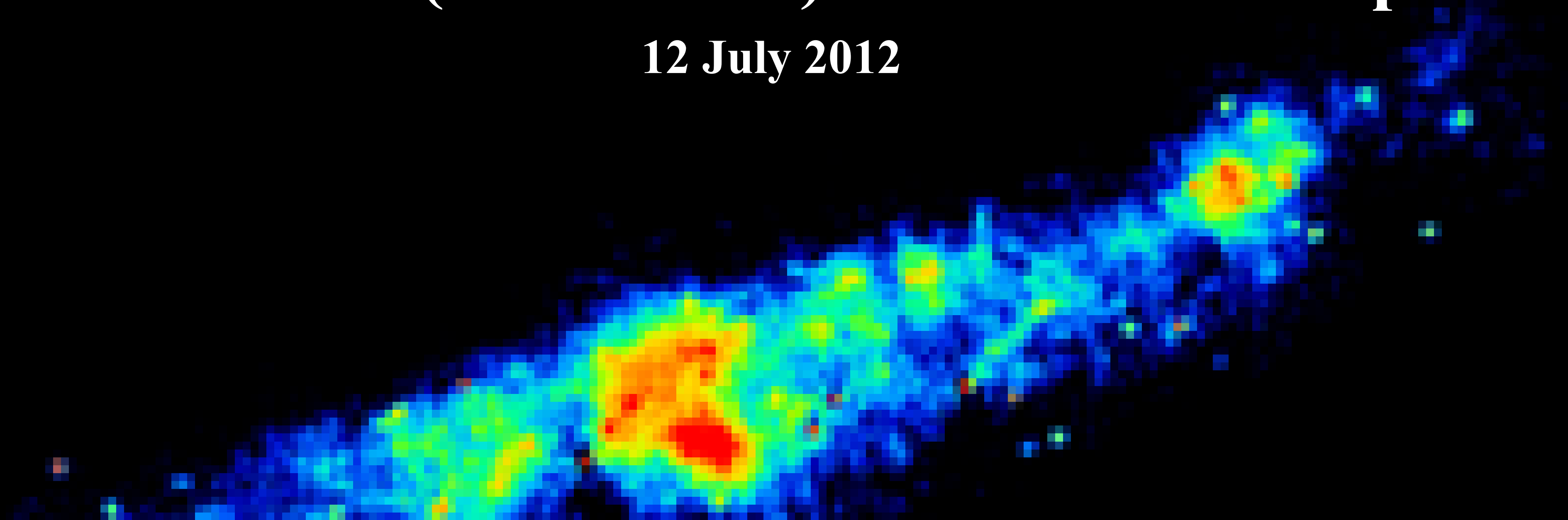
12 July 2012



Infrared

Star Formation

CO Emission

Gas

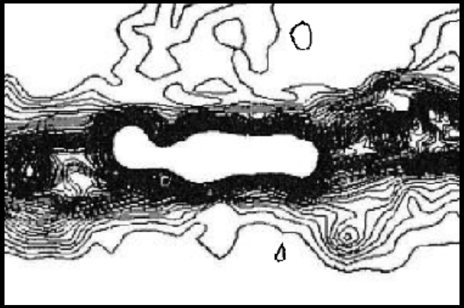
Radio

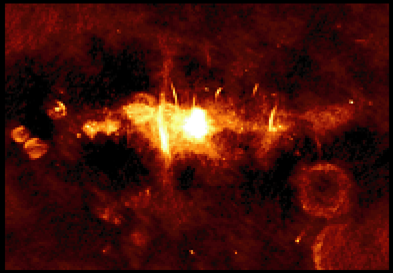
Magnetic fields
+ CR electrons

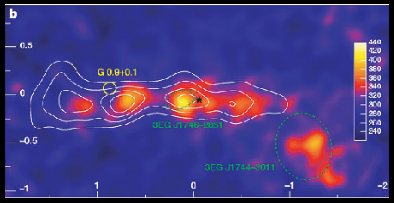
Gamma-rays

Gas + CR
protons

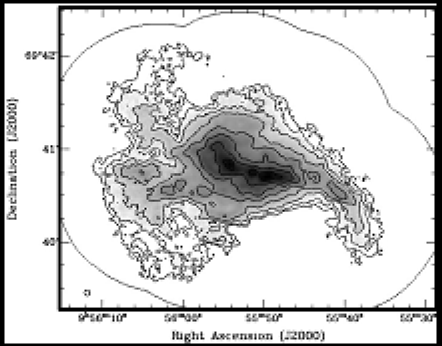
Galactic Center

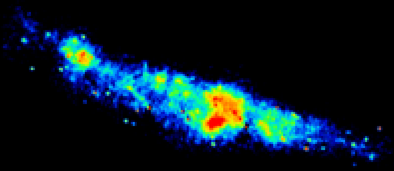


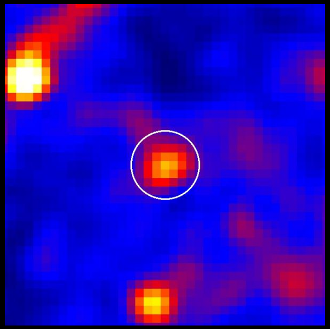




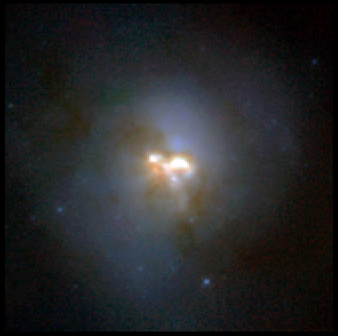
M82

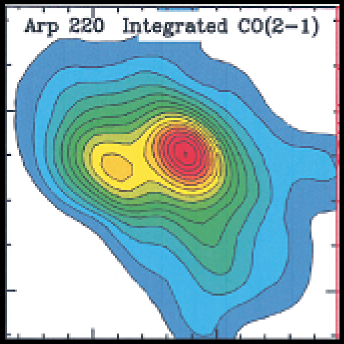


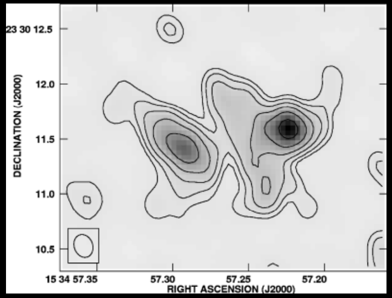


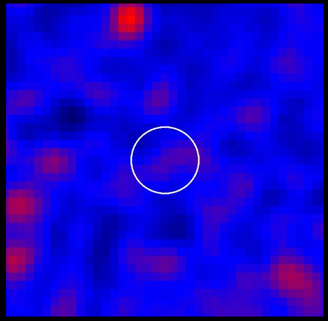


Arp 220



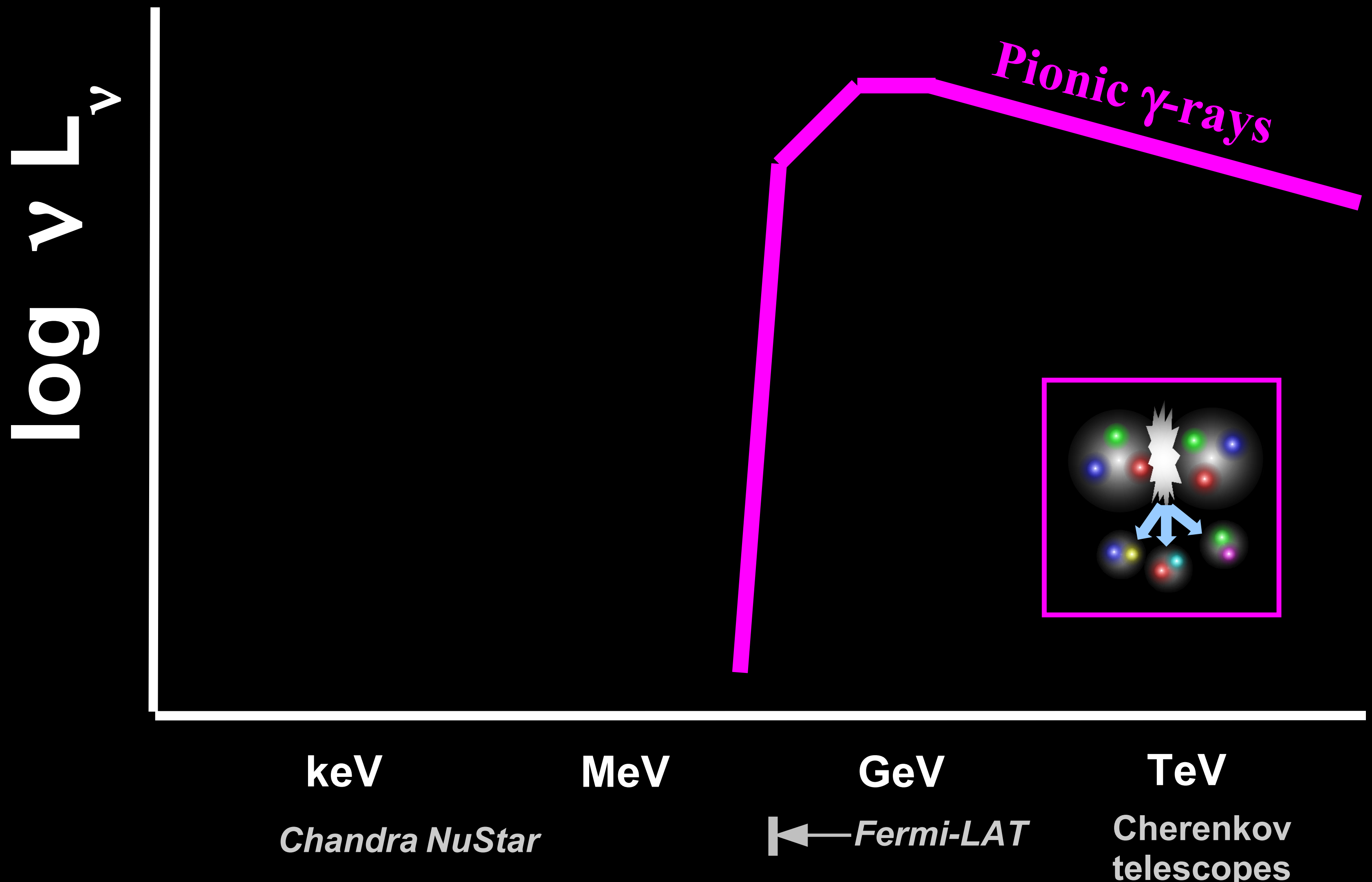




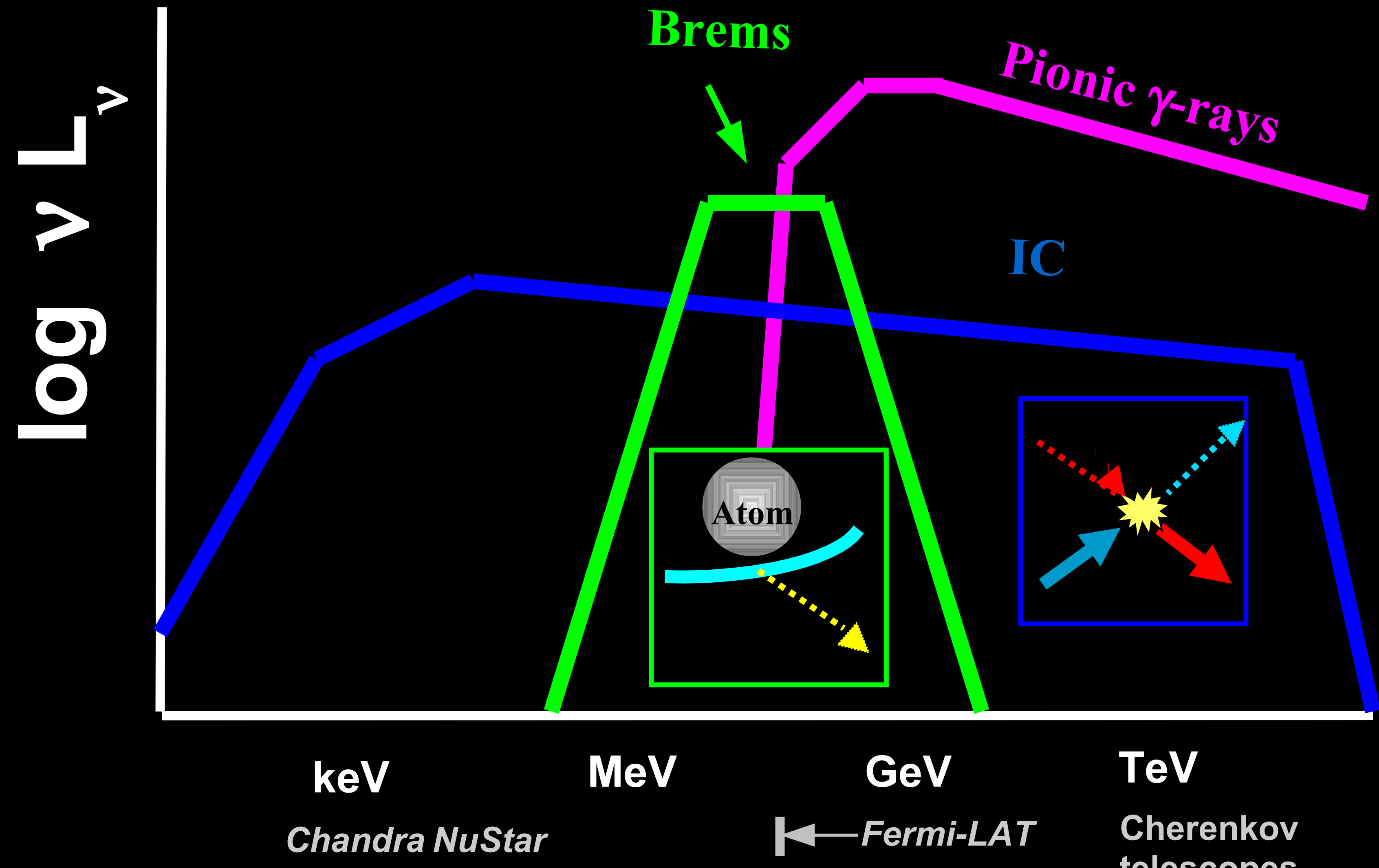


Spitzer ; Dame et al. 1987; Kassim et al.; Aharonian et al. (2006). ; Spitzer; Walter, Weiss, & Scoville (2002); Muxlow et al.; WISE; Downes & Solomon (1998); Rovilos et al. (2003);

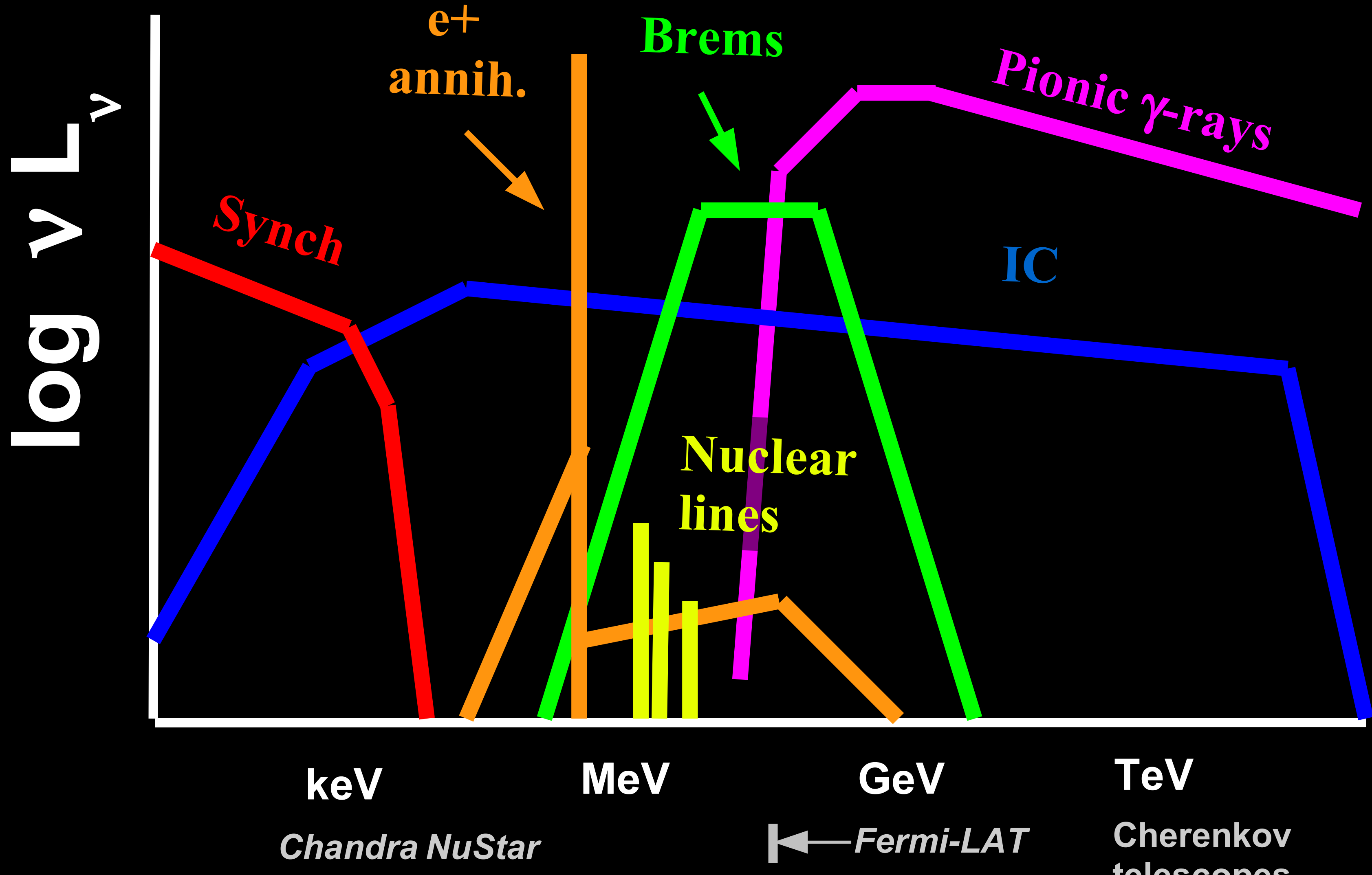
High Energy Emission from CRs



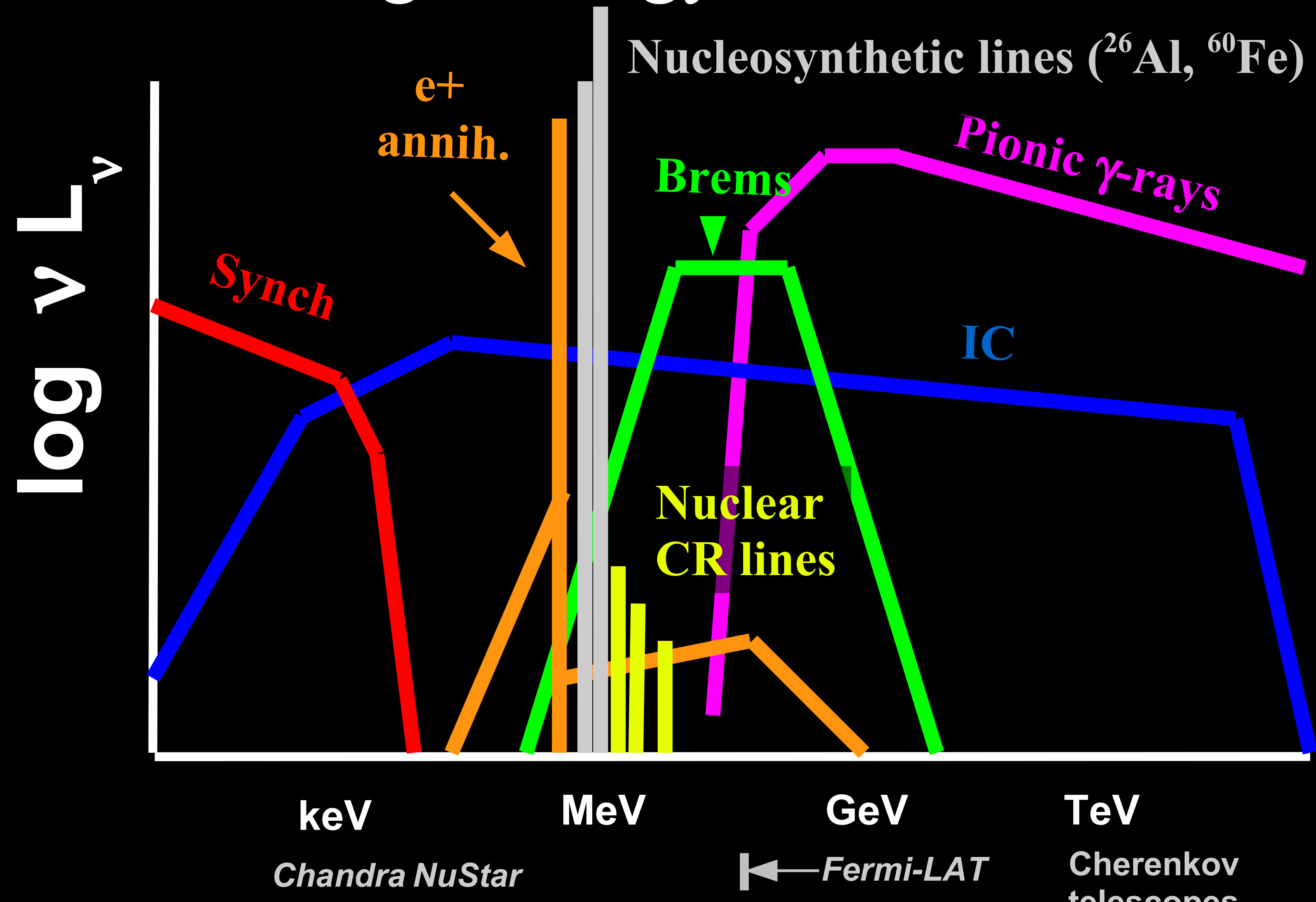
High Energy Emission from CRs



High Energy Emission from CRs



High Energy Emission



What is a Starburst?

High star-formation rate?

Then most cosmic SF in starbursts

Rapid SFR from galaxy merger?

Then only ~5-15% of cosmic SF in starbursts

Things with large SFR density Σ_{SFR}?

Then large fraction (most?) of cosmic SF in starbursts

The FIR-Gamma Ray Correlation?

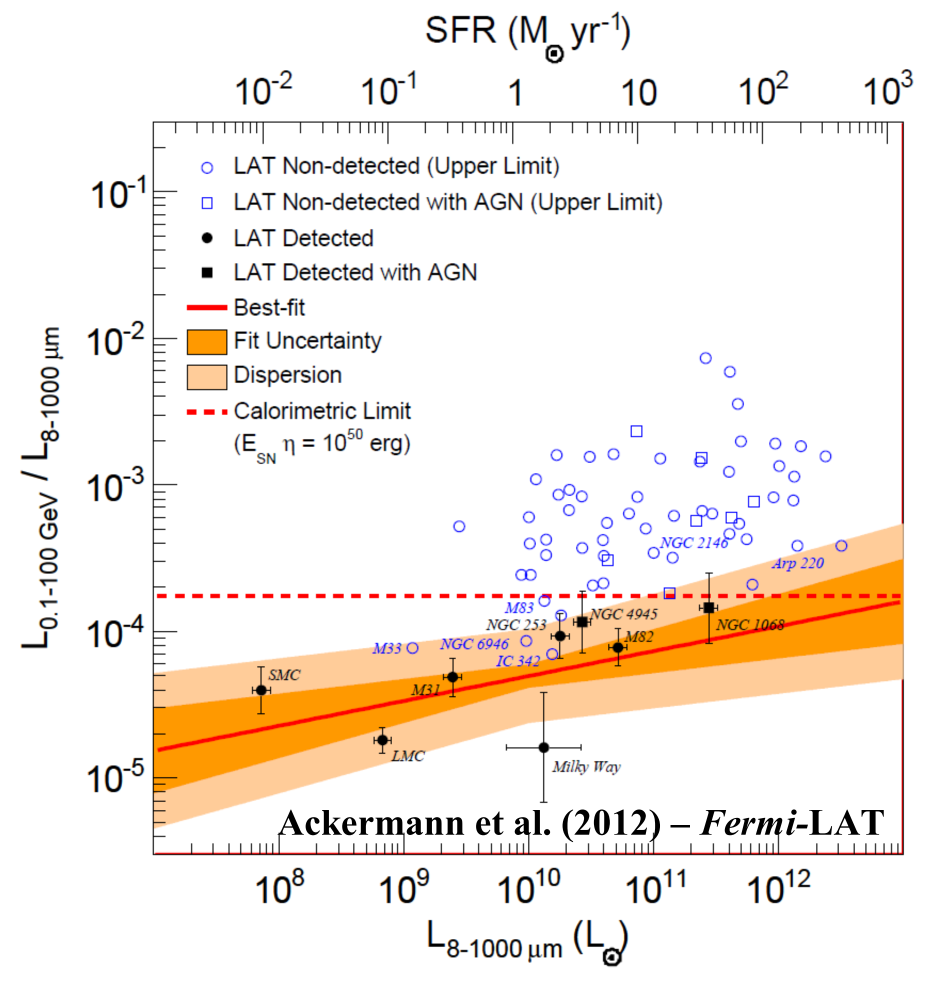
γ-ray

↑

IR -- γ-ray ratio

↓

IR



Ackermann et al. (2012) – *Fermi*-LAT

IR Luminosity (***not density***) →

The Calorimetry Fraction

$$\mathbf{F_{cal} \sim 0.3\ (observed)}$$

$$\mathbf{F_{cal} \sim L_{\pi} / L_{CR} \sim 3\ L_{\gamma} / L_{CR}}$$

$$F_{cal} = (1 + t_{wind}/t_{\pi})^{-1} \sim 1/2\ \text{(theoretical)}$$

$$t_{wind} \sim h / v \sim 200\ \text{kyr}\ (v / 300\ \text{km s}^{-1})^{-1}$$

$$t_{\pi} \sim 200\ \text{kyr}\ (n / 250\ \text{cm}^{-3})^{-1}$$

Assumes that gamma-rays are pionic

Much higher than Milky Way (~1 – 10%)

Probably not fully calorimetric, but many uncertainties

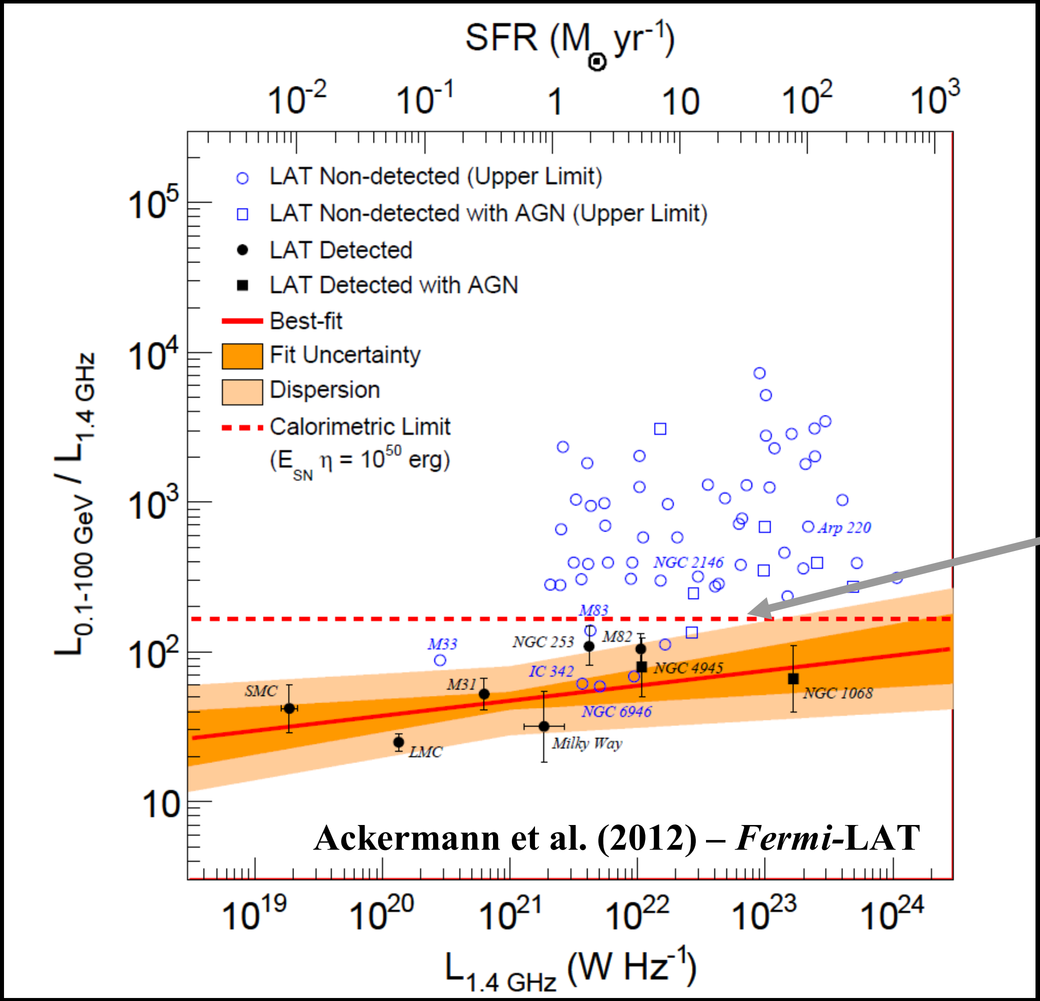
May be a sign of winds

Comparing Radio to Gamma Rays

γ-ray

Radio-γ-ray ratio

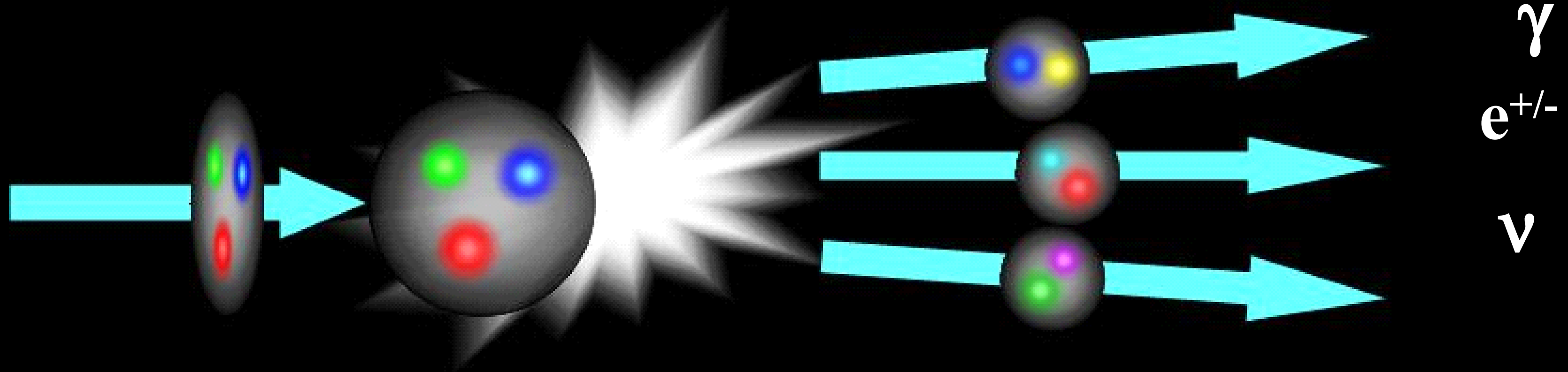
Radio



Ackermann et al. (2012) – *Fermi*-LAT

Starbursts are dozens of times brighter in γ-rays than in radio

Secondary $e^{+/-}$



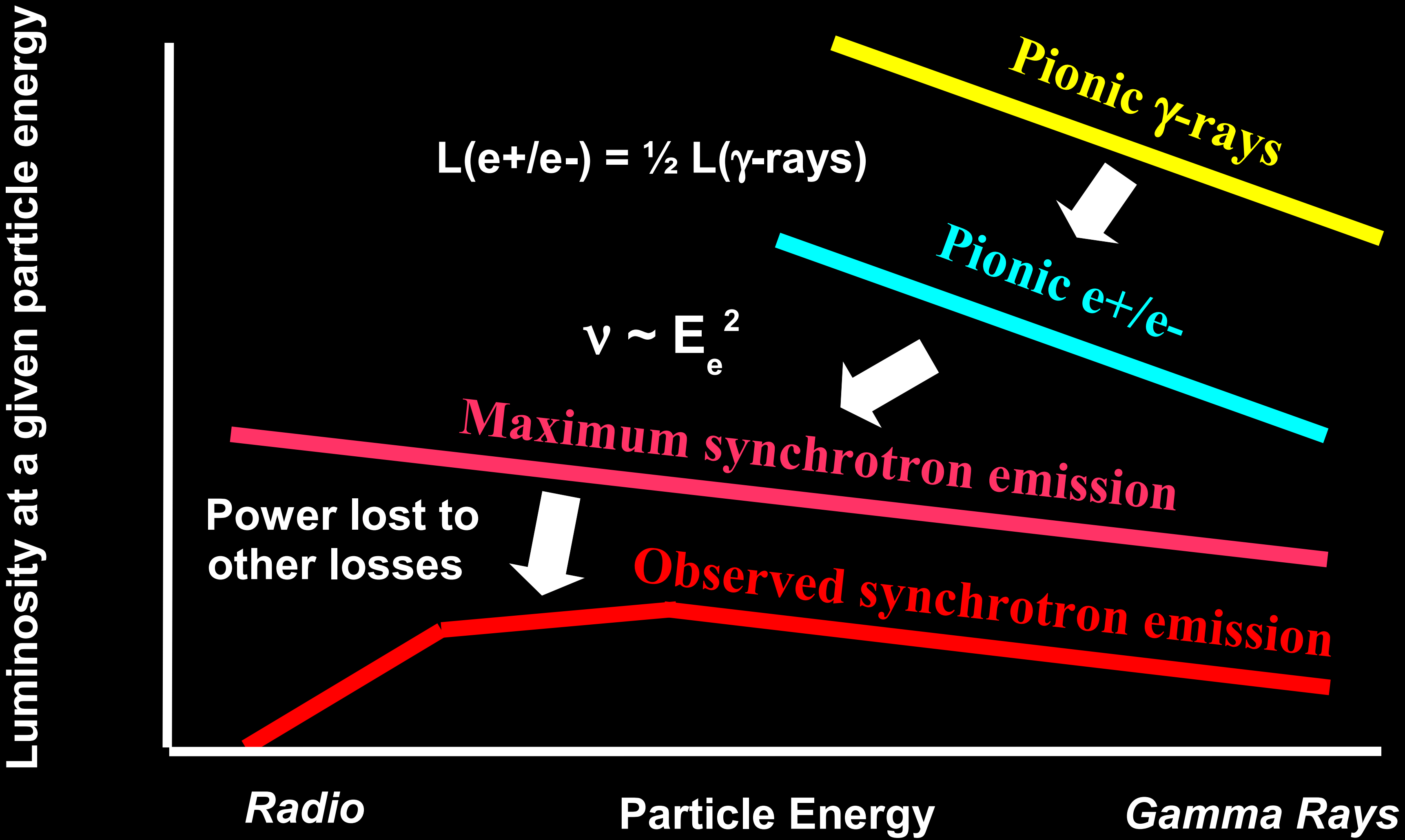
Cosmic ray protons hit ISM protons and make pions

$$
\begin{array}{lllllllll}
\pi^+ & \rightarrow & e^+ & + & \nu_e & + & \bar{\nu}_\mu & + & \nu_\mu \\
\pi^- & \rightarrow & e^- & + & \bar{\nu}_e & + & \nu_\mu & + & \bar{\nu}_\mu \\
\pi^0 & \rightarrow & & & \gamma & + & \gamma & &
\end{array}
$$

Secondary e+/e-

Gamma-rays & neutrinos

Comparing Radio to Gamma Rays



Pionic γ-rays

$L(e+/e-) = \frac{1}{2} L(\gamma\text{-rays})$

Pionic e+/e-

$\nu \sim E_e^2$

Maximum synchrotron emission

Power lost to other losses

Observed synchrotron emission

Luminosity at a given particle energy

Radio

Particle Energy

Gamma Rays

Comparing Radio to Gamma Rays

$$\nu L_\nu \text{ (GeV } \gamma) \sim 4\, f_{synch}\, \nu L_\nu \text{ (GHz)}$$

$$\mathbf{f_{synch}\ (M82) \sim 1/8}$$

$$\mathbf{f_{synch}\ (NGC\ 253) \sim 1/8 - 1/17}$$

Assumes that gamma-rays are pionic

Strong support for a conspiracy setting radio luminosity

f_{synch} even smaller if radio is partly from primaries

Does equipartition hold in M82 and NGC 253?

U_{CR} (>GeV) ~ 200 eV cm^{-3} (250 cm^{-3}/n)

U_B ~ 1000 eV cm^{-3} (B / 200 μG)^2

U_{FIR} ~ 200 – 1000 (1 + τ_{FIR}) eV cm^{-3}

$P_{hydro} = \pi G \Sigma_g \Sigma_{tot} \sim 5000\, f_{gas}^{-1}$ eV cm^{-3}

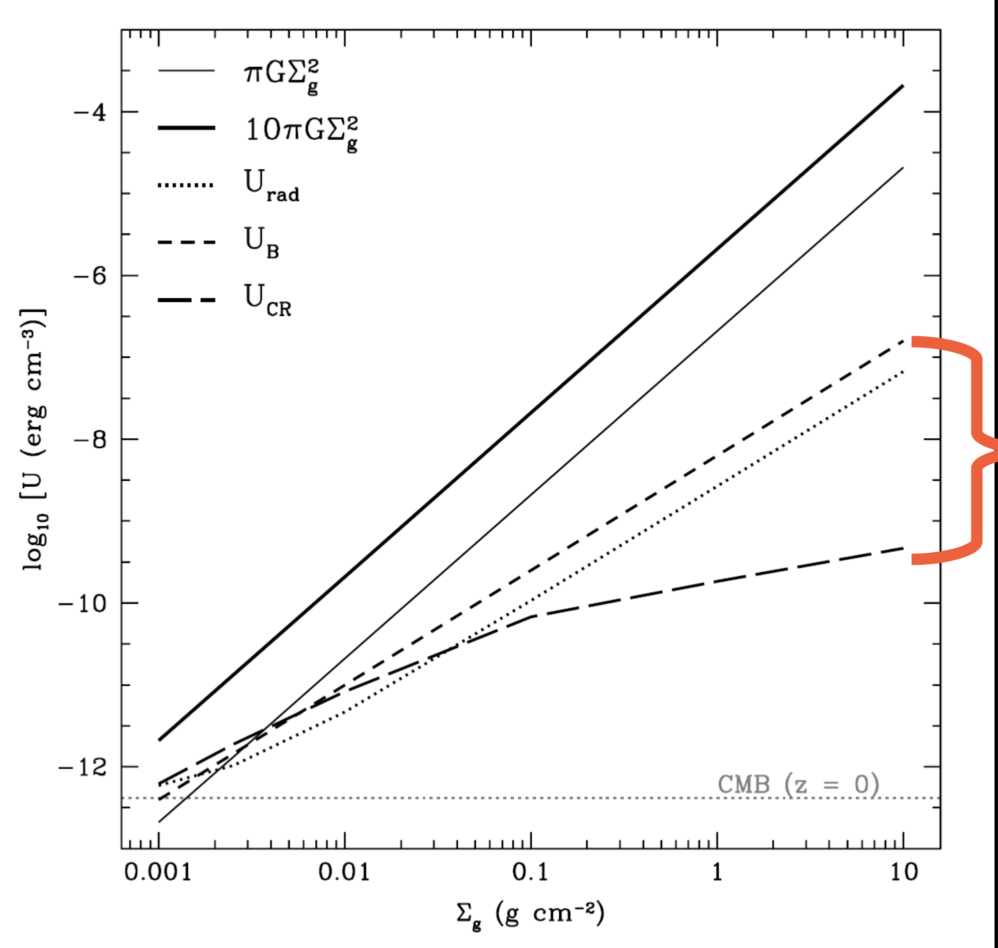
P_{therm} ~ 300 - 1700 eV cm^{-3} (neutral clouds, HII region)

P_{turb} ~ 26000 eV cm^{-3} (diffuse ionized)

Thermal and turbulent pressures from Lord et al. (1996), Smith et al. (2006)

Should Equipartition Hold?

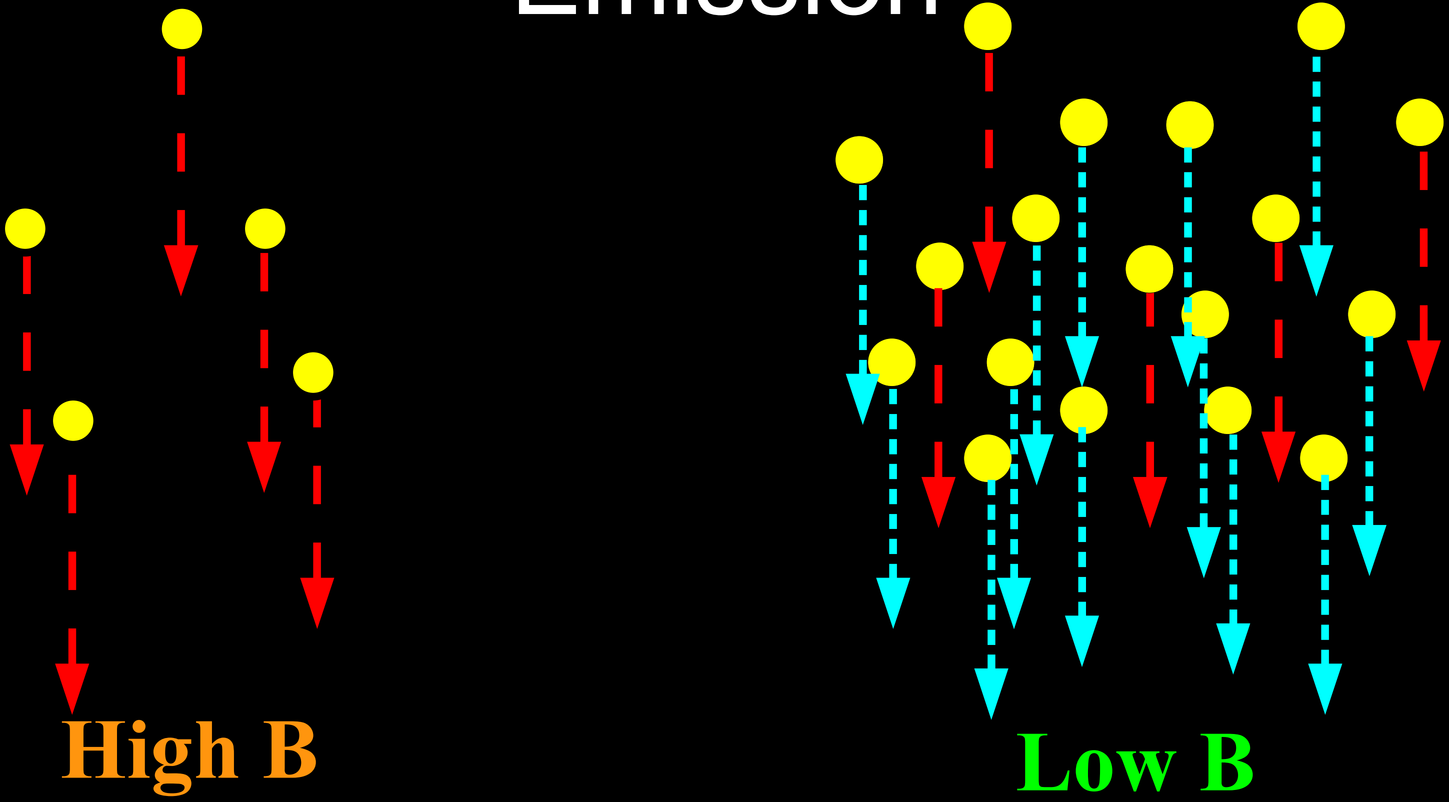
Energy Density



Pion losses convert CR protons to gamma-rays, neutrinos, e+/-

Equipartition between B and CRs fails in dense starbursts

Constraints on B from Leptonic Emission

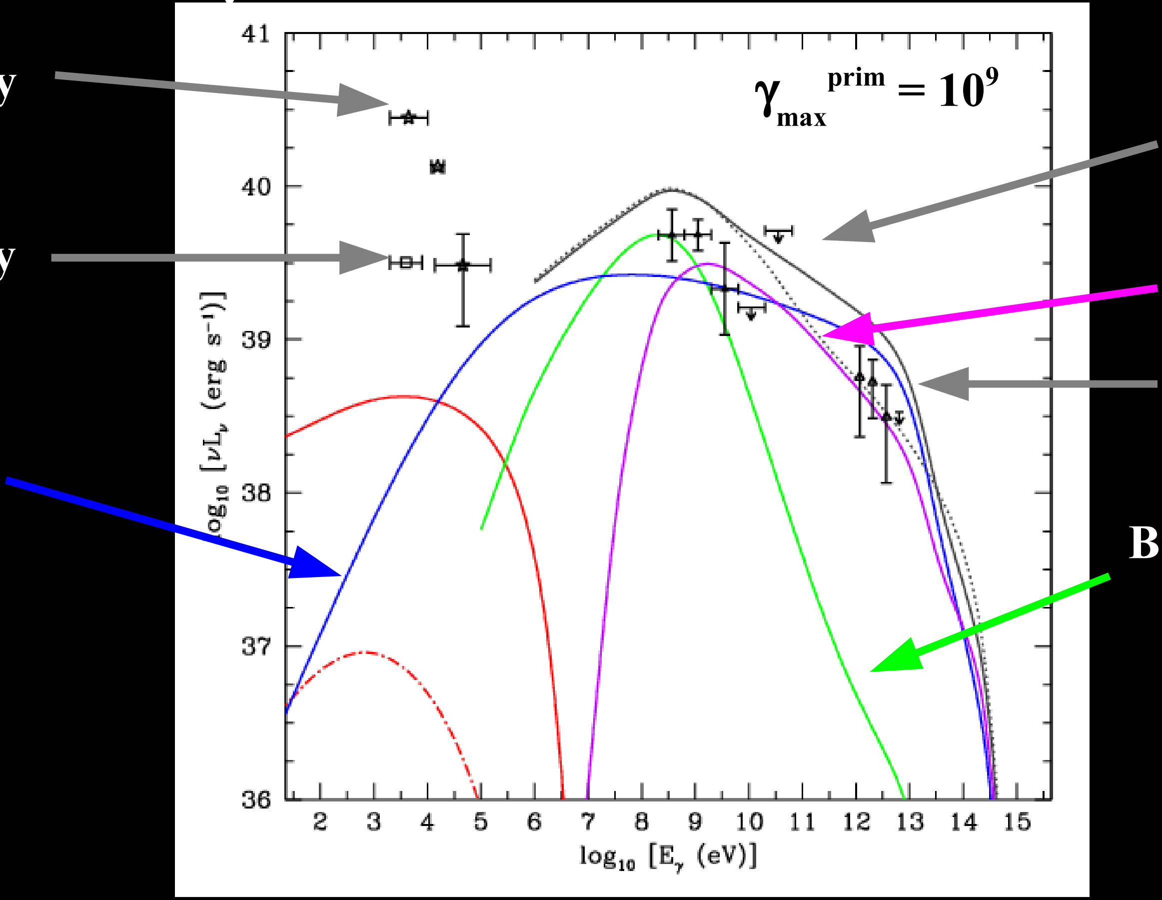


If B is low, then radio emission implies many electrons, implying much leptonic emission

Crocker et al. (2010) – Galactic Center B >~ 50 μG

Neutrinos eventually give hadronic emission.

50 μG model for M82



Total X-ray emission

Diffuse X-ray emission

Inverse Compton emission

Fermi-LAT detections

Pionic emission

VERITAS detections

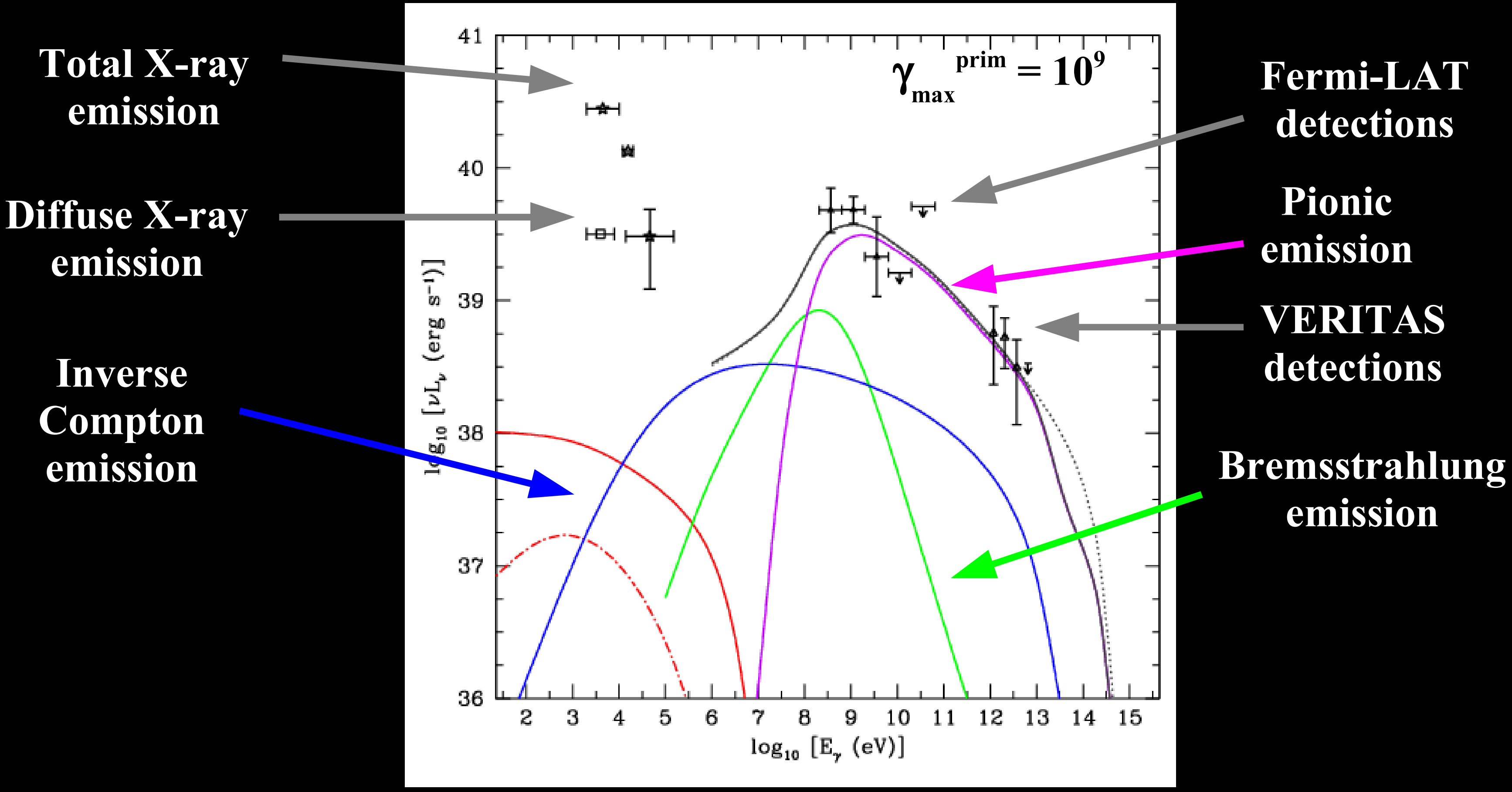
Bremsstrahlung emission

GeV – TeV gamma-rays constrain IC at keV: IC is broad continuum

Requires primary p/e ratio ~ 1 instead of ~100

Similar results for NGC 253

150 μG model for M82



Total X-ray emission

Diffuse X-ray emission

Inverse Compton emission

Fermi-LAT detections

Pionic emission

VERITAS detections

Bremsstrahlung emission

GeV – TeV gamma-rays constrain IC at keV: IC is broad continuum

Primary p/e ratio closer to Milky Way value, ~50

Similar results for NGC 253

Cosmic Ray Ionization

CRs may play crucial role in ionization in starbursts

UV light heavily extinguished

X-rays from AGN not always present

Much higher density of CRs => higher ζ

$$\zeta_{CR} \sim 10^{-15} - 10^{-14}\ s^{-1}\ \text{(ULIRGs)}$$

Would ensure ionization in molecular gas => magnetic fields

Heats gas to 50 – 150 K

“Cosmic Ray Dominated Regions” (Papadopoulos 2010)

But what if CRs reach all of molecular gas?

Gamma Rays to the Rescue

$$Z + \gamma \rightarrow Z + e^{+} + e^{-}$$

Gamma Ray Dominated Regions

Proton calorimetry produces gamma rays

L_{γ} up to L_{CR} / 3

Gamma rays are *not* deflected by magnetic fields

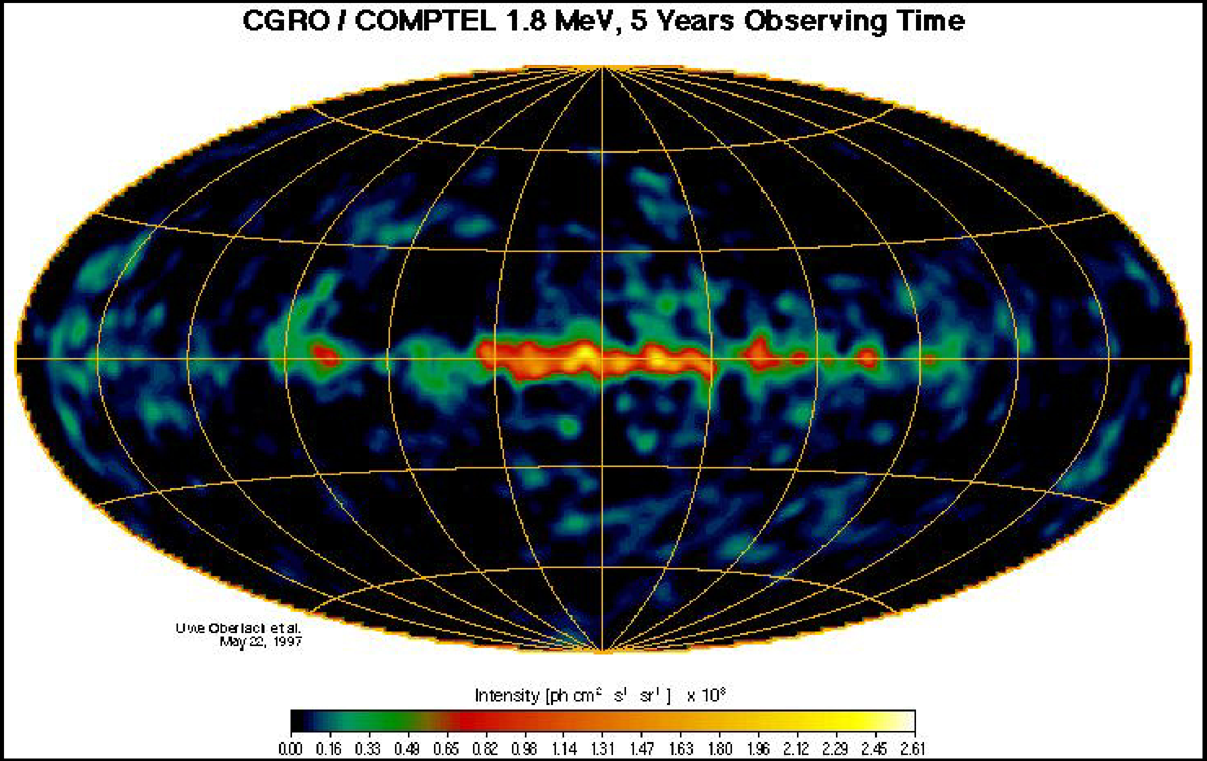
Can penetrate columns of ~200 g/cm^2

$$\zeta_{\gamma} = F_{\gamma}\, \sigma_{\gamma Z}\, f_{ion} / E_{ion}$$

In densest starbursts, like Arp 220

$$\zeta_{\gamma} \sim 10^{-17}\ s^{-1}$$

The Galaxy's Nuclear Waste



Massive stars generate radioactive isotopes

^{26}Al is the most prominent

Credit: COMPTEL Collaboration

Starbursts are Radioactive

$$\mathbf{X(^{26}Al) \sim M(^{26}Al) / M_H \sim SFR / M_H \sim 1/\tau_{gas}}$$

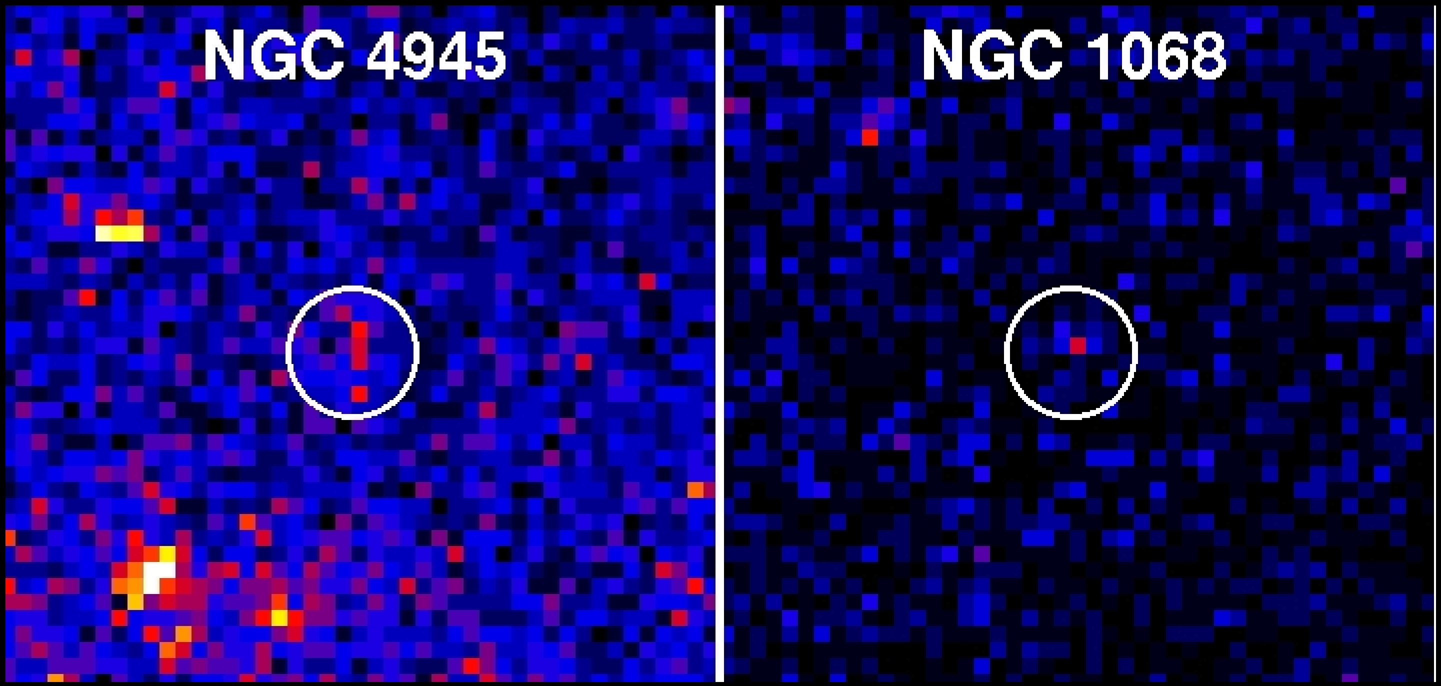
τ_{gas} is ~100 times shorter in starbursts

^{26}Al abundances are ***100*** times higher

$$\mathbf{^{26}Al / ^{27}Al \sim 10^{-3}}$$

$$\mathbf{\zeta(^{26}Al) \sim 10^{-18} – 10^{-17}\ s^{-1}}$$

NGCs 4945 & 1068: Seyferts or Starbursts?

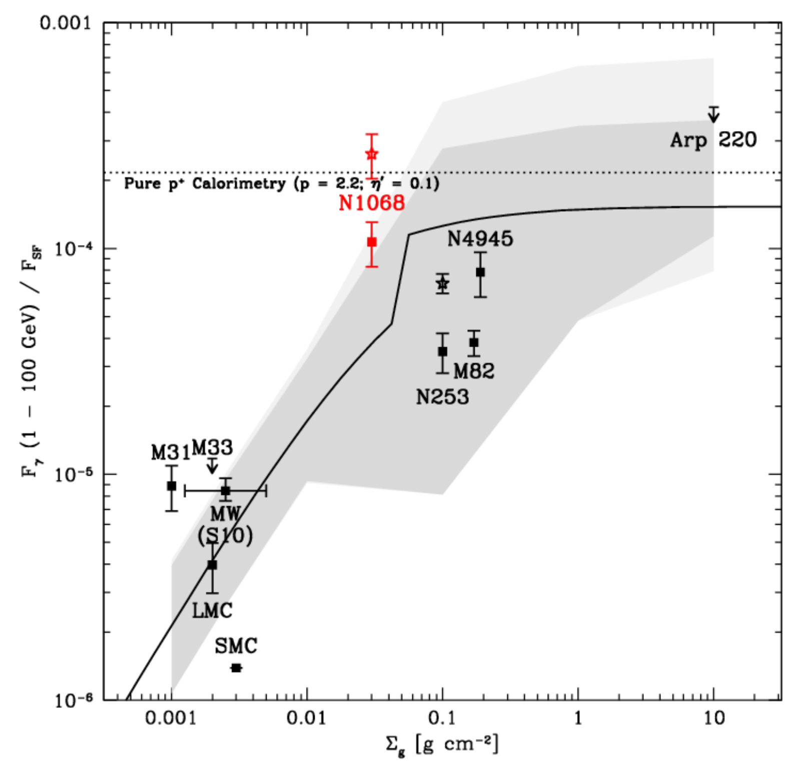


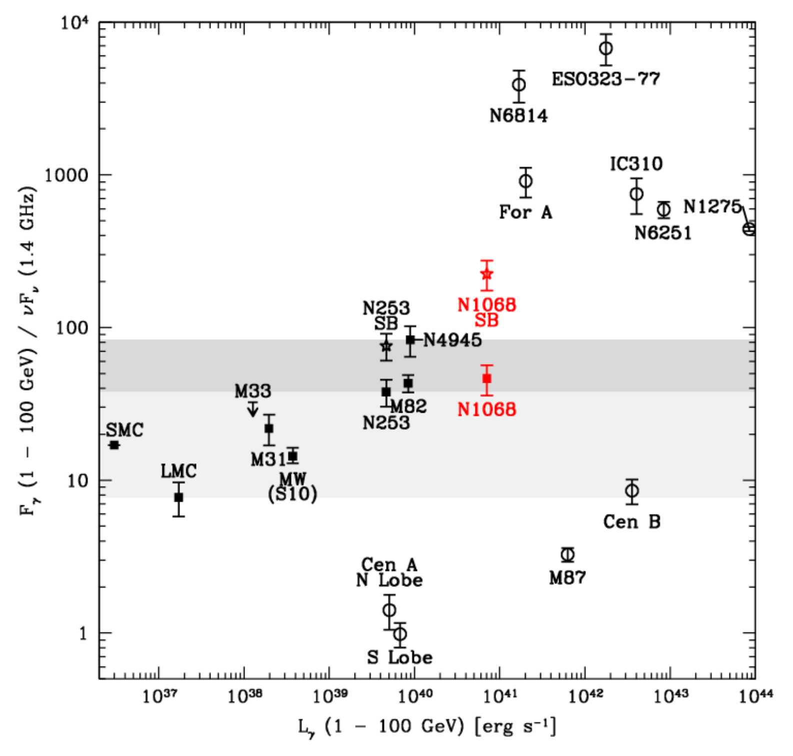
γ-ray flux is within order of magnitude of predictions for starbursts

γ-ray spectral index with *Fermi* is ~2.2

γ-rays apparently constant with time

Is NGC 1068 a Starburst?





NGC 1068 looks γ-ray bright by a factor ~2 – 5

Is it really IC emission from an AGN (Lenain et al. 2010)

Hadronic AGN emission? (Lacki & Thompson in prep)

PWNe?

High SFR => Many supernovae => Many PWNe

If the pionic emission falls off from diffusion, emission from PWNe may stick out (Mannheim et al. 2012)

$$E_{PSR} / E_{CR} \sim 10^{49}\ \mathrm{erg} / 10^{50}\ \mathrm{erg} \sim 0.1$$

In MW, g-ray efficiency is low, but starbursts may be different

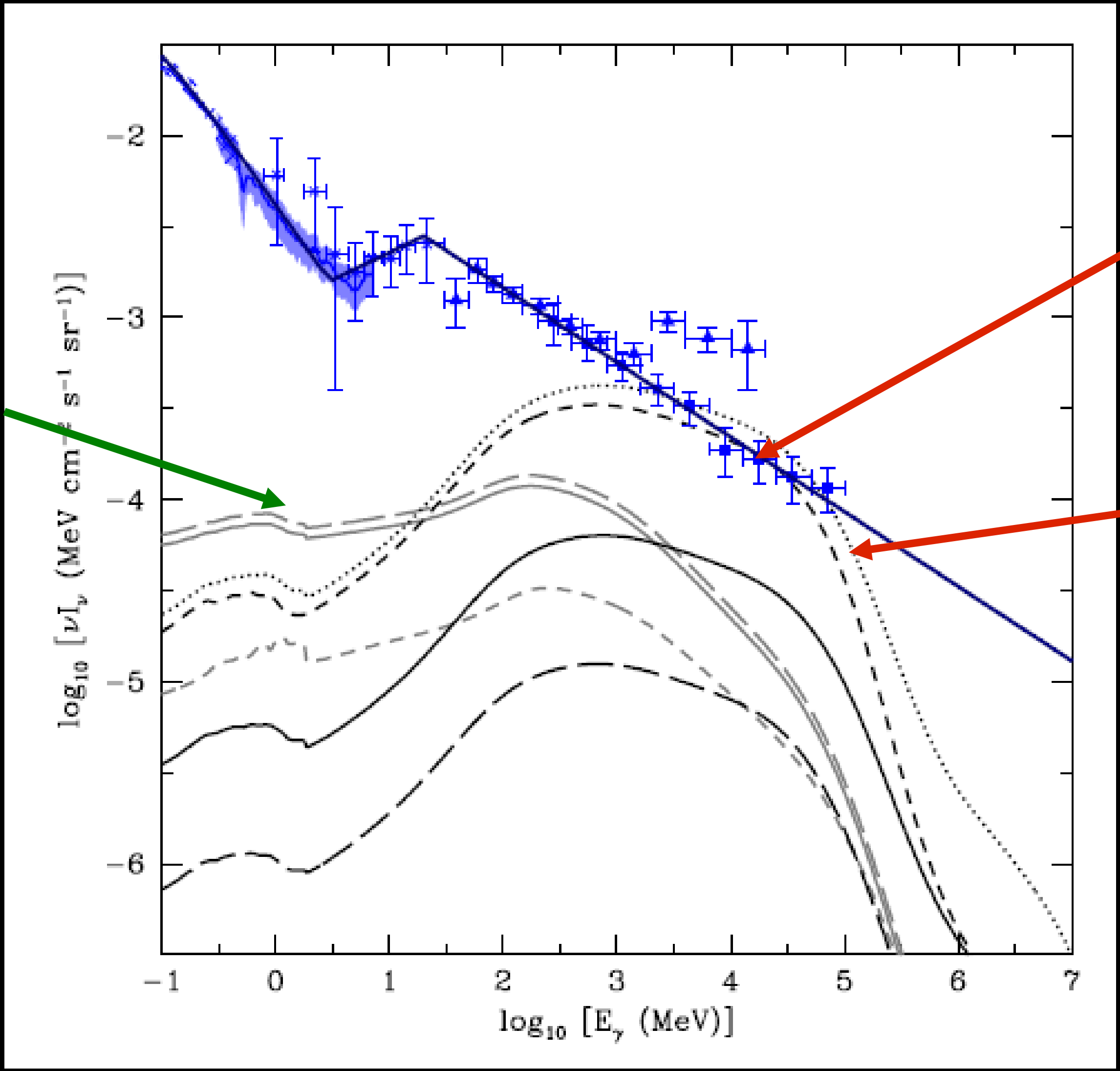
In M82 and NGC 253, $U_{rad} \sim 1000$ eV cm^{-3}

$$t_{IC} \sim 300\ \mathrm{yr}\ (E / \mathrm{TeV})^{-1}$$

In Arp 220 starburst nuclei, $U_{rad} \sim 10^5$ eV cm^{-3}

$$t_{IC} \sim 3\ \mathrm{yr}\ (E / \mathrm{TeV})^{-1}$$

The γ-ray Background



Background from MW-like galaxies

Starbursts have hard γ-ray spectra

If most cosmic SFR in "starbursts", then they are most of the 1 – 100 GeV background

Opportunities with CTA

Many starbursts should be visible with CTA

Get good high quality spectra

- Look for transition to diffusion
- Look for $\gamma\gamma$ absorption dip from IR radiation

Would include Arp 299 and Arp 220

- Very high density (10 – 100x M82 and NGC 253)
- Fully proton calorimetric?
- Equipartition between CRs and B fails?

What about Neutrinos?

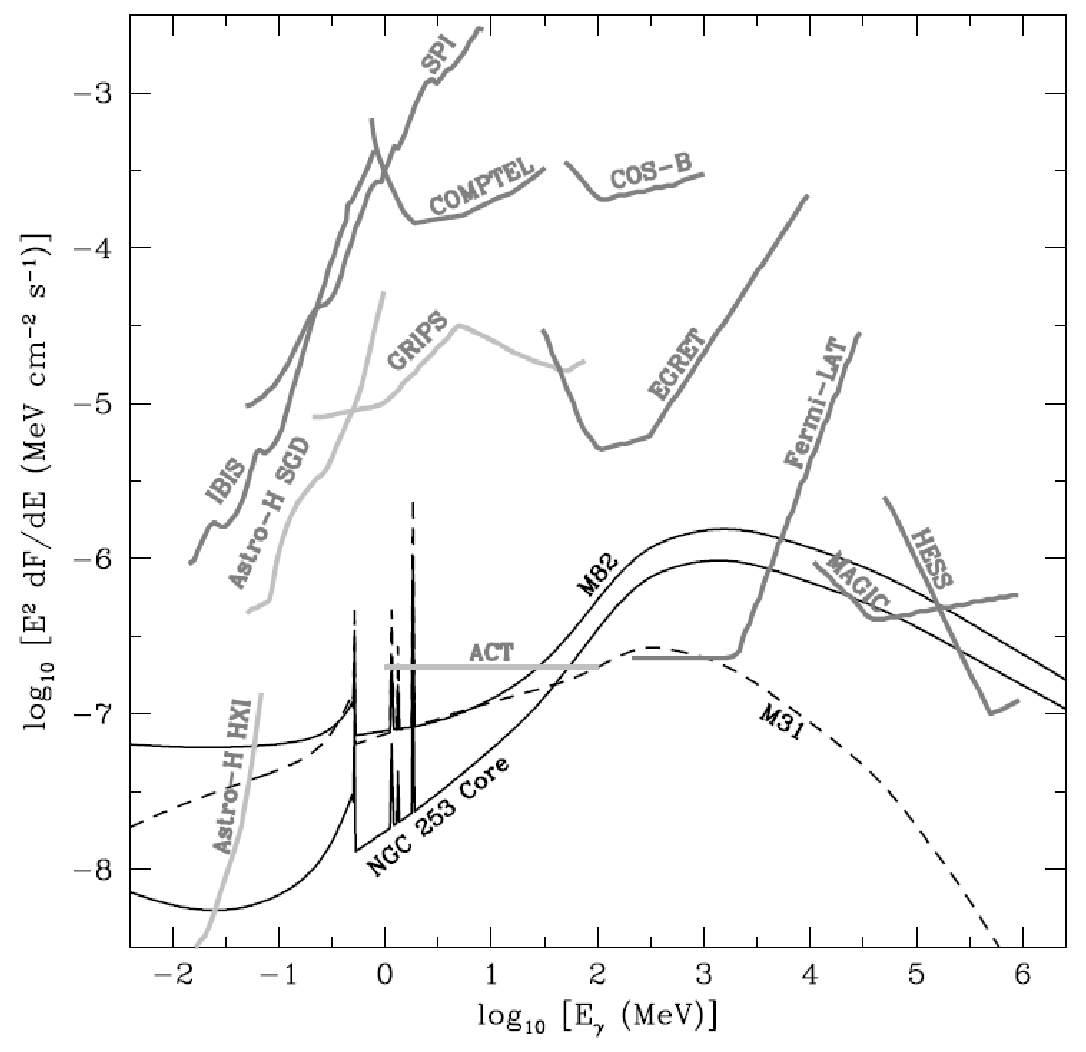
Pionic γ-rays necessarily imply pionic neutrinos

- Would be direct proof of CR acceleration
- Constrain other g-ray emission

Difficulties

- Proton spectrum ends at ~PeV => n spectrum ends at 50 TeV
- Starbursts have $E^{-2.2}$ spectrum instead of $E^{-2.0}$ spectrum
- Unfortunate placement of starbursts on sky
  - M82 at very high declination – low sensitivity
  - NGC 253 and 4945 in Southern hemisphere
- Relatively faint sources
  - NGC 1068: >~7 years / ν with IceCube

The Sorrow of MeV Astronomy



Conclusion

γ-rays probe the bulk of the CRs in starbursts

- Starbursts have high CR energy densities
- Large minority of CR power converted into pions
- Small minority of electron power into synchrotron
  - Constraints on B

CRs can shape starbursts

- Cosmic ray ionization far larger than in Milky Way
- γ-rays and radioactive elements may ionize

Problems and opportunities

- Role of AGNs, PWNe
- γ-ray background source?
- Outlook good for CTA, but νs and MeV γ-rays hard