HE emission from star-forming galaxies

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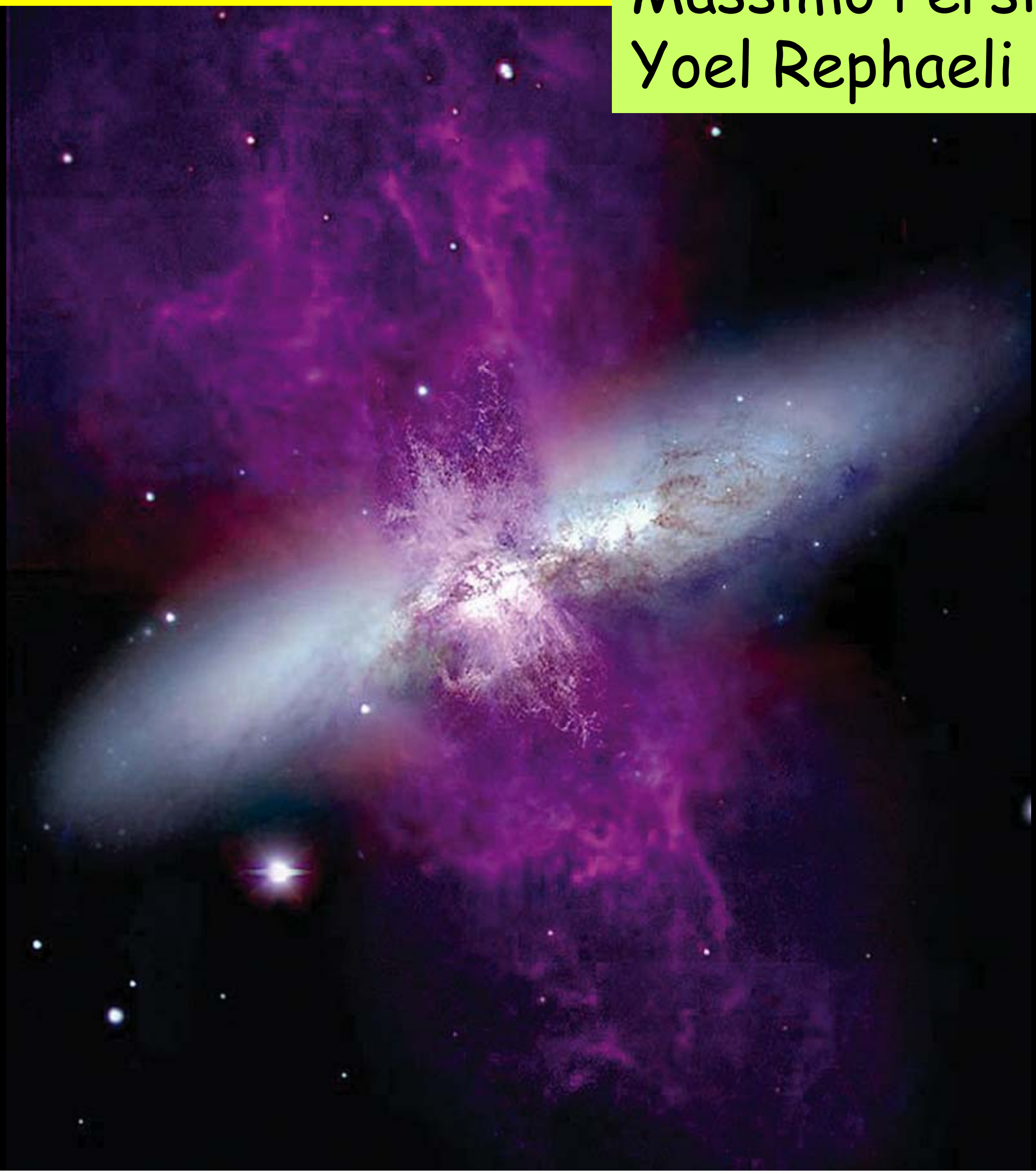
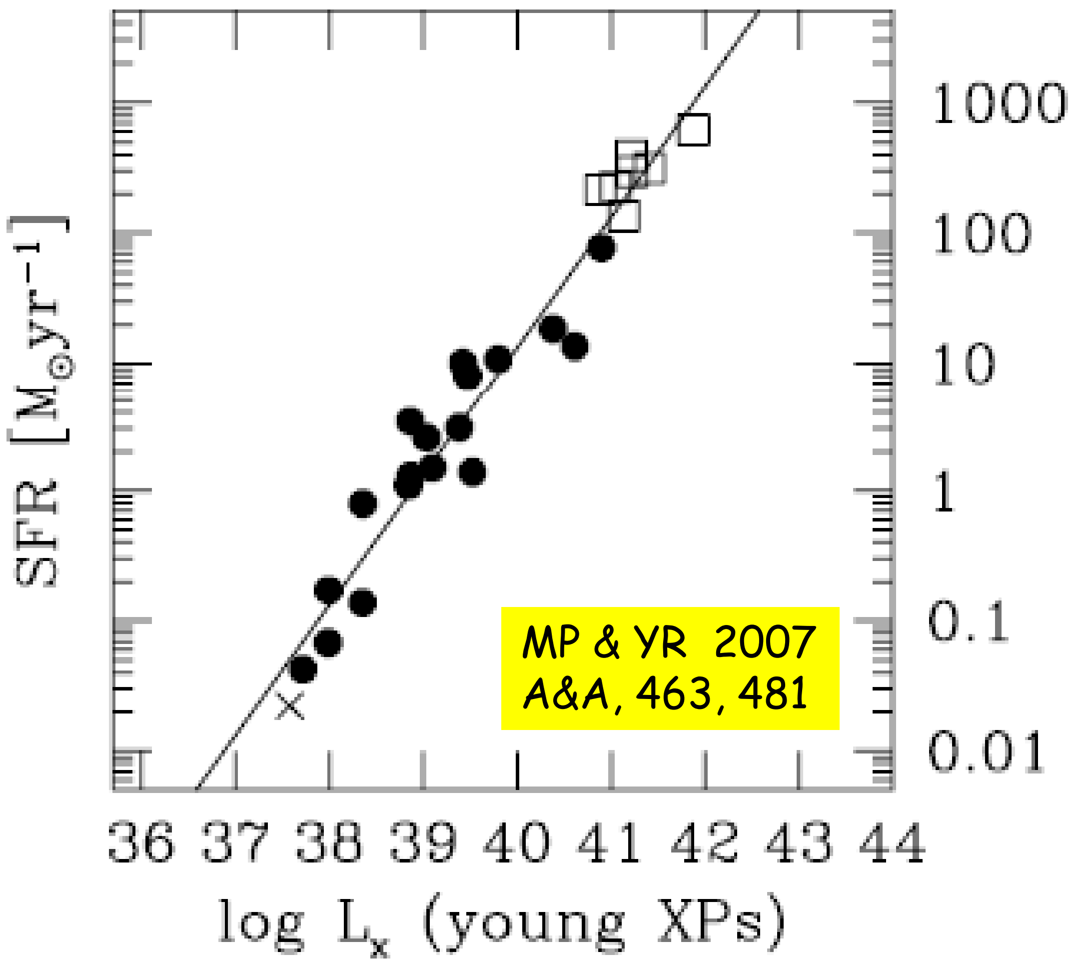




FIR, X-ray emission: tracers of massive SF

gal's powered by current SF

high SN rate

Gauging particle spectra from radio emission

NT radio emission → CRe → CRp → (equip.) → B, U_p

$N_e(\gamma) = N_{e,0}\, \gamma^{-q}$ $\quad \gamma_1 \le \gamma \le \gamma_2$ $\quad \ldots\ \gamma_1 = 100$

$F_\nu = 5.67\times10^{-22}\, (r_s^{3}/d^{2})\, N_{e,0}\, a(q)\, B^{(q+1)/2}\, (\nu/4\times10^{+6})^{-(q-1)/2}$ $\quad$ erg/(s cm^2 Hz)

$$\psi \equiv \left(\frac{r_s}{0.1\,\mathrm{kpc}}\right)^{-3} \left(\frac{d}{\mathrm{Mpc}}\right)^{2} \left(\frac{f_{1\,\mathrm{GHz}}}{\mathrm{Jy}}\right)$$

$$N_{e,0} = 5.72\times10^{-15}\,\psi\, a(q)^{-1} B^{-\frac{q+1}{2}}\, 250^{\frac{q-1}{2}}$$

$$U_e = N_{e,0} m_e c^2 \int_{\gamma_1}^{\gamma_2} \gamma^{1-q} d\gamma = 2.96\times10^{-22}\, 250^{\frac{q}{2}}\, \psi\, \frac{\gamma_1^{-q+2}}{(q-2)\, a(q)}\, B^{-\frac{q+1}{2}}$$

$$\kappa \equiv \frac{U_p}{U_e} = \frac{\int_{T_0}^{\infty} N_p(T)\, T\, dT}{\int_{T_0}^{\infty} N_e(T)\, T\, dT}$$

$$U_p + U_e \simeq \frac{B^2}{8\pi}$$

$$B_{eq} = \left[7.46\times10^{-17}\, \frac{(2.5\times10^{-2})^{q/2}}{q-2}\, \psi\, \frac{1+\kappa(q)}{a(q)}\right]^{\frac{2}{5+q}}$$

T_0=few keV

$$\kappa \equiv \frac{U_p}{U_e} = \frac{\int_{T_0}^{\infty} N_p(T)\, T\, dT}{\int_{T_0}^{\infty} N_e(T)\, T\, dT} =$$

$$= \frac{\left[\frac{T_0^2}{c^2}+2T_0 m_p\right]^{\frac{q-1}{2}} \int_{T_0}^{\infty} T(T+m_p c^2)\left[\frac{T^2}{c^2}+2T m_p\right]^{-\frac{q+1}{2}} dT}{\left[\frac{T_0^2}{c^2}+2T_0 m_e\right]^{\frac{q-1}{2}} \int_{T_0}^{\infty} T(T+m_e c^2)\left[\frac{T^2}{c^2}+2T m_e\right]^{-\frac{q+1}{2}} dT}$$

$$\frac{N_p(T)}{N_e(T)} \simeq \left(\frac{m_p}{m_e}\right)^{\frac{q-1}{2}} \left(\frac{T+m_p c^2}{T+m_e c^2}\right) \left(\frac{T+2m_p c^2}{T+2m_e c^2}\right)^{-\frac{q+1}{2}}$$

$$\simeq \begin{cases} 1 & T << m_e c^2\,; \\ [T/(m_e c^2)]^{\frac{q-1}{2}} & m_e c^2 << T << m_p c^2 \\ (\frac{m_p}{m_e})^{\frac{q-1}{2}} & m_p c^2 << T\,. \end{cases}$$

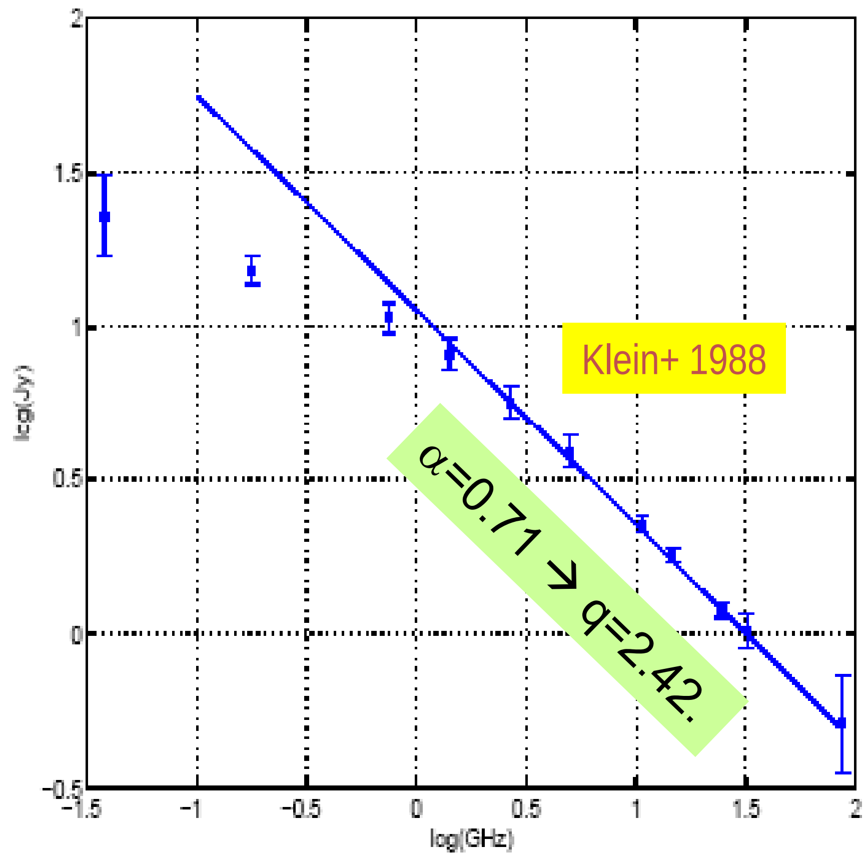
q=2.3 → $\kappa = U_p/U_e \approx 15$ $N_p/N_e|_{>>1GeV} \approx 1.3 \times 10^2$

M 82

Persic, Rephaeli & Arieli
2008, A&A, 486, 143

parameters: d=3.6 Mpc
r(starburst)= 300 pc
f_{1GHz} = 10 Jy
α=0.71 → q=2.42

$$B \simeq 95\mu G$$
$$N_{e,0} \simeq 10^{-4} \ \ cm^{-3}$$
$$U_e \simeq 20 \ \ eV\ cm^{-3}$$
$$U_p \simeq 200 \ \ eV\ cm^{-3}$$



M82: VHE γ-ray emission

… approximate treatment

$$L(\geq \epsilon) = \int_V g(\geq \epsilon)\, n\, U_p\, dV \quad s^{-1}$$

α	$q_\gamma(\geq 100\,\mathrm{MeV})$	$q_\gamma(\geq 1\,\mathrm{TeV})$
4.1	0.46×10^{-13}	1.02×10^{-17}
4.2	0.58×10^{-13}	4.9×10^{-18}
4.3	0.61×10^{-13}	2.1×10^{-18}
4.4	0.57×10^{-13}	8.1×10^{-19}
4.5	0.51×10^{-13}	3.0×10^{-19}
4.6	0.44×10^{-13}	1.0×10^{-19}
4.7	0.39×10^{-13}	3.7×10^{-20}

Drury+ 1994

SB nucleus: r≤0.3 kpc

$M_{H2} = 2\times10^8\ M_\otimes$

$U_p = 200\ \mathrm{eV\ cm^{-3}}$

$L_{>100GeV} = 1.6\times10^{39}\ s^{-1}$ → $F_{>100GeV} = 10^{-12}\ cm^{-2}\ s^{-1}$

External disk: r>0.3 kpc

Gas: flat, thin, exponential disk: $\Sigma(R) = \Sigma(0)\, e^{-R/R_d}$

$\Sigma(0) = 7.5E{+}22\ cm^{-2}$

$R_d = 0.82$ kpc

$M_g = 2.5\times10^9 M_\otimes$

$U_p = 200\ (R/R_{SB})^{-2}$

$L_{>100GeV} = 1.5\times10^{40}\ s^{-1}$ → $F_{>100GeV} = 10^{-11}\ cm^{-2}\ s^{-1}$

→ Total flux from M82: $\mathbf{F_{>100GeV} = 1.1\times10^{-11}\ cm^{-2}\ s^{-1}}$

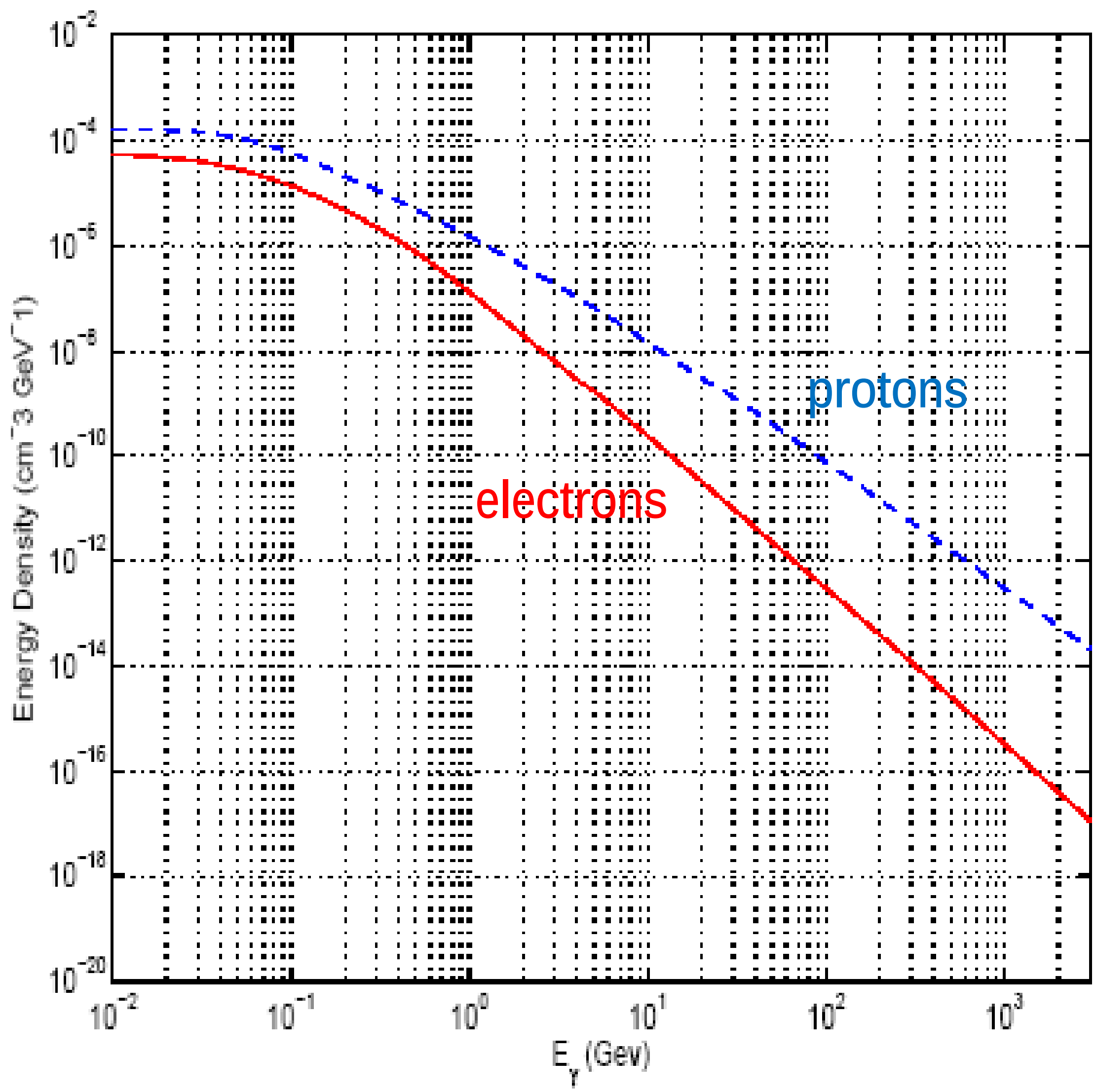
... numerical treatment

... same structure parameters, mag. flux frozen in ionized gas ($B \propto n_{HII}^{-3/2}$)

1. Radio synchrotron em. → $B \oplus N_e$

2. Particles vs Field → energy equipartiton

injection part. spectrum: q=2
... interactively →
$N_e \sim 10^{-4}$ cm^{-3}
N_p/N_e (>>1 GeV) ~ 100,
$B_0 \sim 300$ μG



.. cont'd

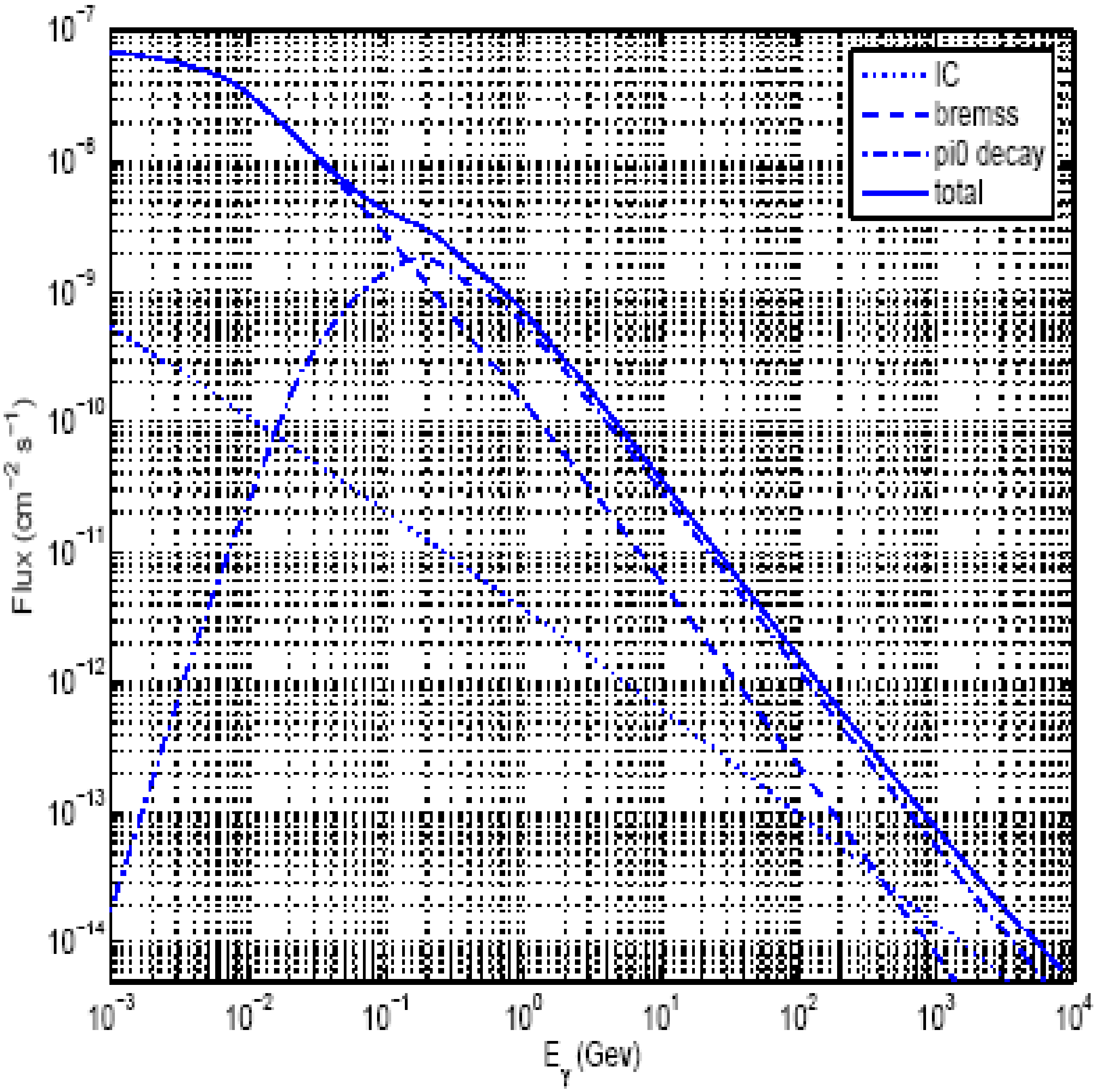
SB nucleus

$F_{>100GeV}$ =
= 1.5×10^{-12} cm^{-2} s^{-1}

$F_{>100MeV}$ =
= 5×10^{-9} cm^{-2} s^{-1}

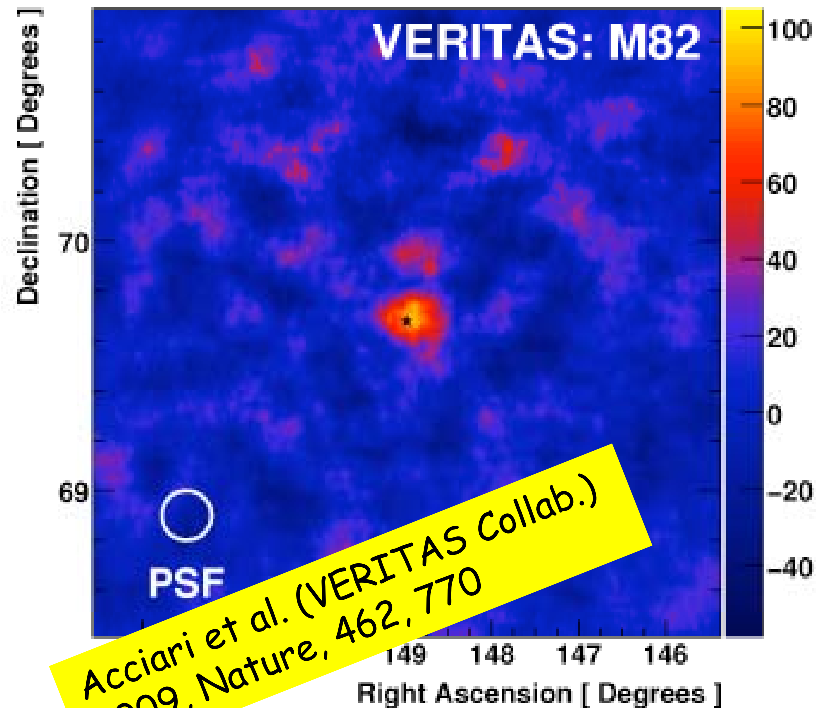
Whole galaxy

$F_{>100GeV}$ =
= 3.5×10^{-12} cm^{-2} s^{-1}

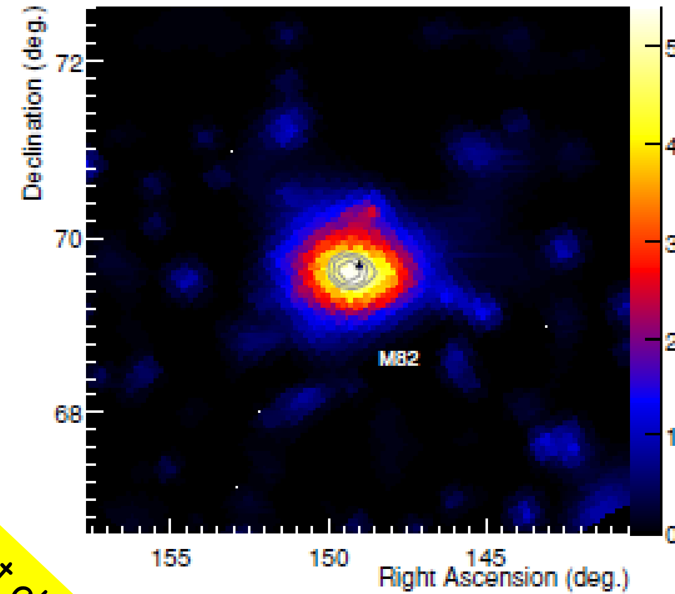


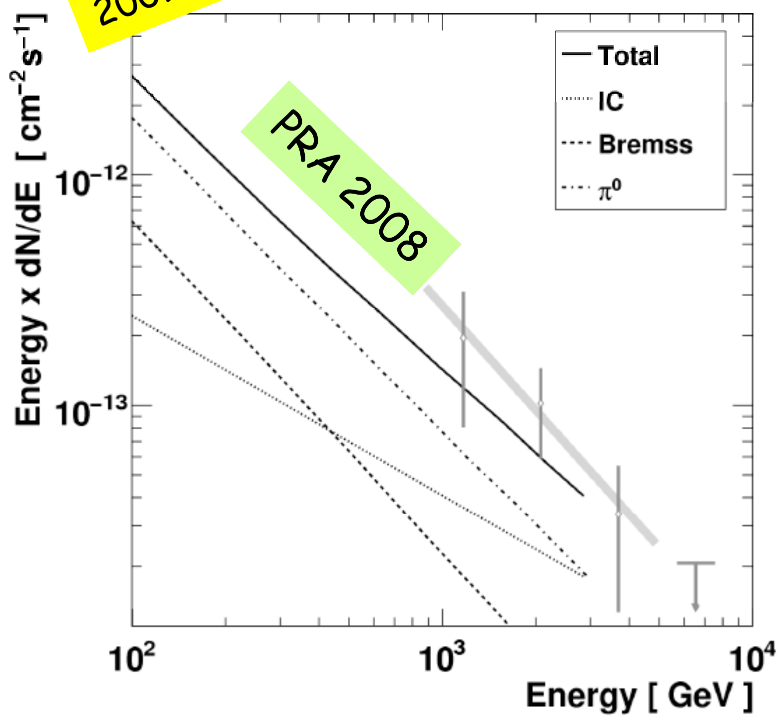
≥1/2 sens. of MAGIC-II, VERITAS

M82 detection

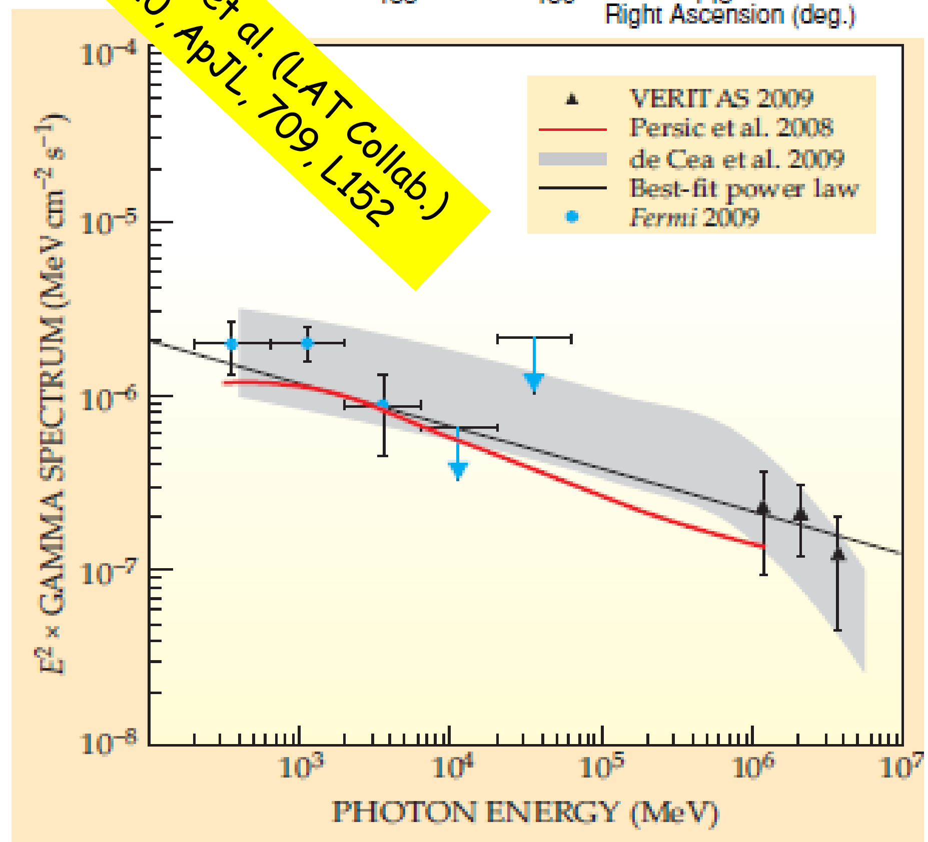


Acciari et al. (VERITAS Collab.) 2009, Nature, 462, 770





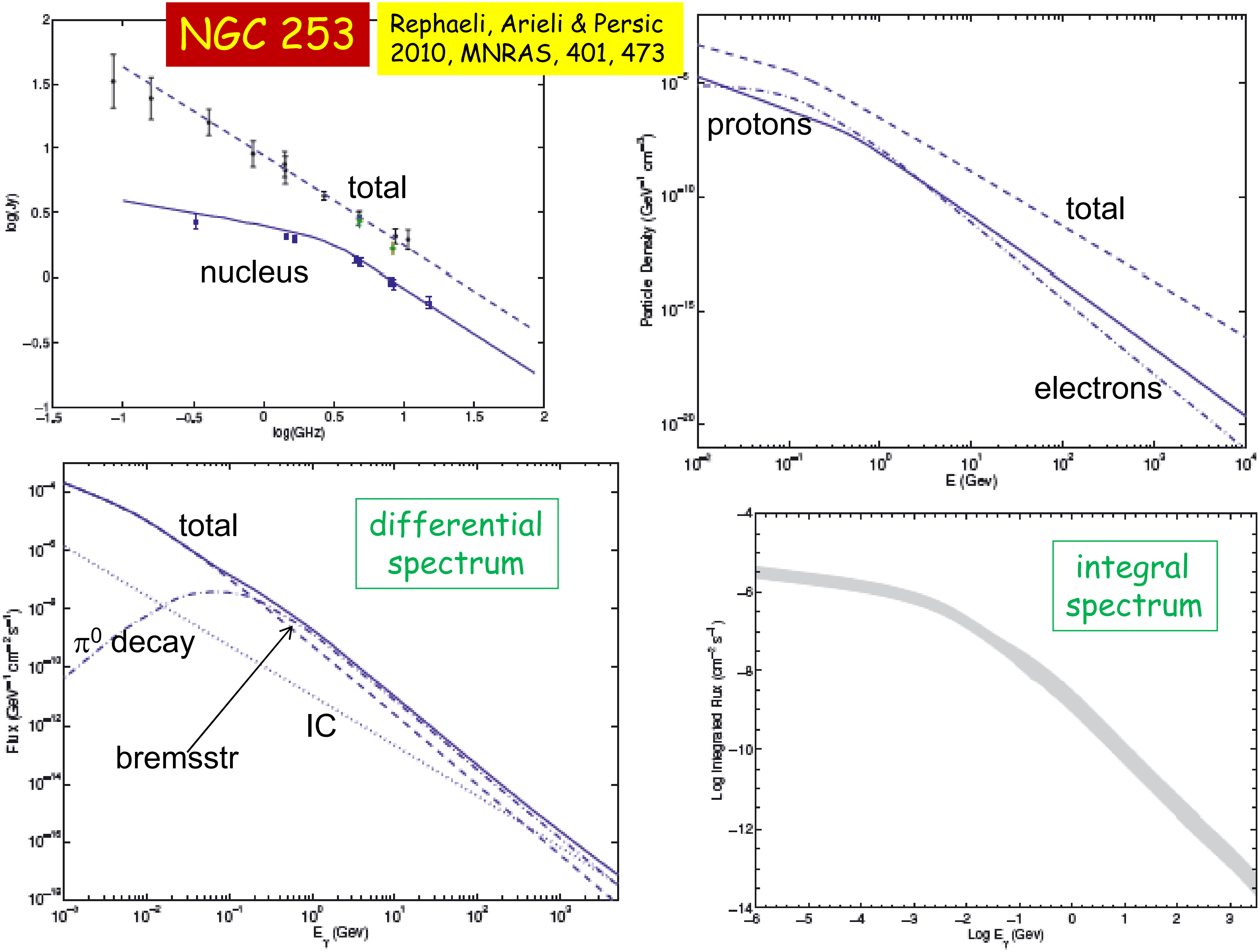
PRA 2008



Abdo et al. (LAT Collab.) 2010, ApJL, 709, L152

NGC 253

Rephaeli, Arieli & Persic
2010, MNRAS, 401, 473

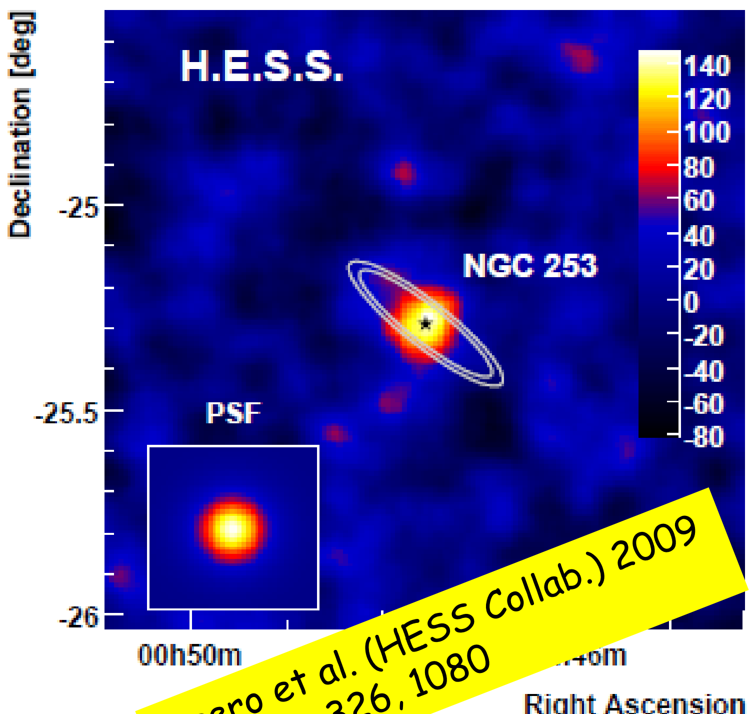


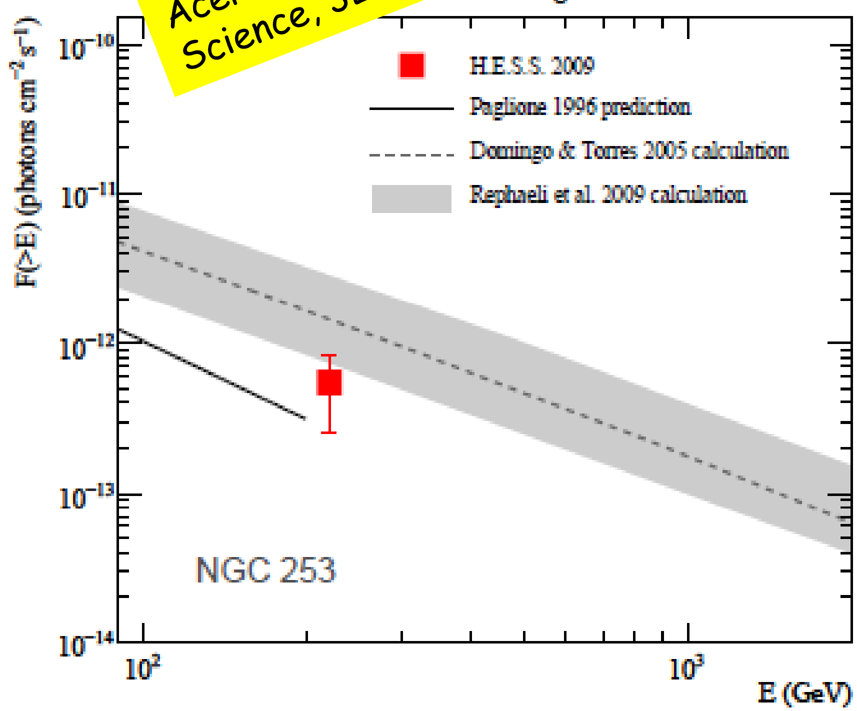
Parameter	Value	Units	Reference
Distance	2.5	Mpc	2
SB region radius	200	pc	6,7
SB region height	150	pc	6,7
Disc radius	10	kpc	
$M_{H2}(R < 1.1\,kpc)$	4.8×10^8	$M_\odot$	8
$M_{H}(R < 600\,pc)$	4.8×10^8	$M_\odot$	2
$M_{H}(R < 10\,kpc)$	2.5×10^9	$M_\odot$	1
$M_{H\,II}(R < 6.35\,kpc)$	2×10^7	$M_\odot$	5
Dust temperature	50 (SB), 16 (disc)	K	3
Dust emissivity index	1.5		3

References to listed data: (1) Boomsma et al. (2005); (2) Bradford et al. (2003); (3) Melo et al. (2002); (4) Sreekumar et al. (1994); (5) Strickland et al. (2002); (6) Paglione et al. (1996); (7) Ulvestad (2000) and (8) Canzian, Mundy & Scoville (1988).

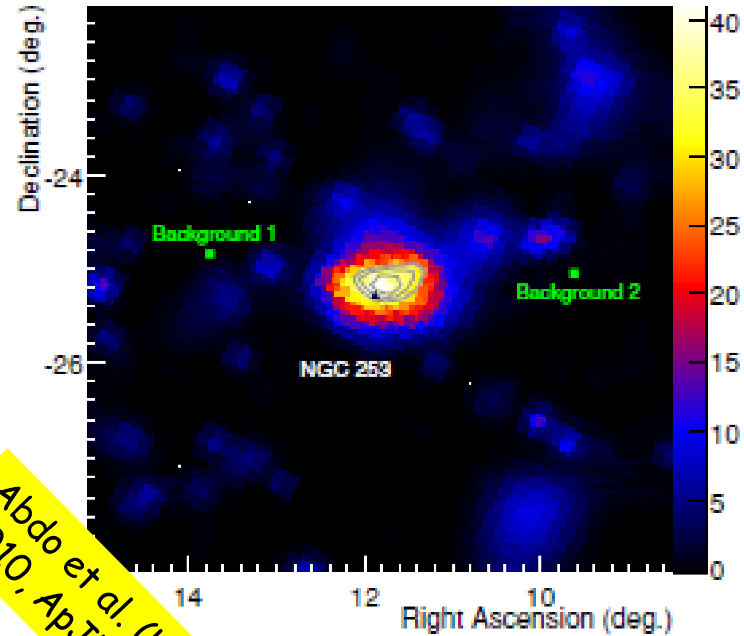
$B_0 \sim 200\ \mu G$

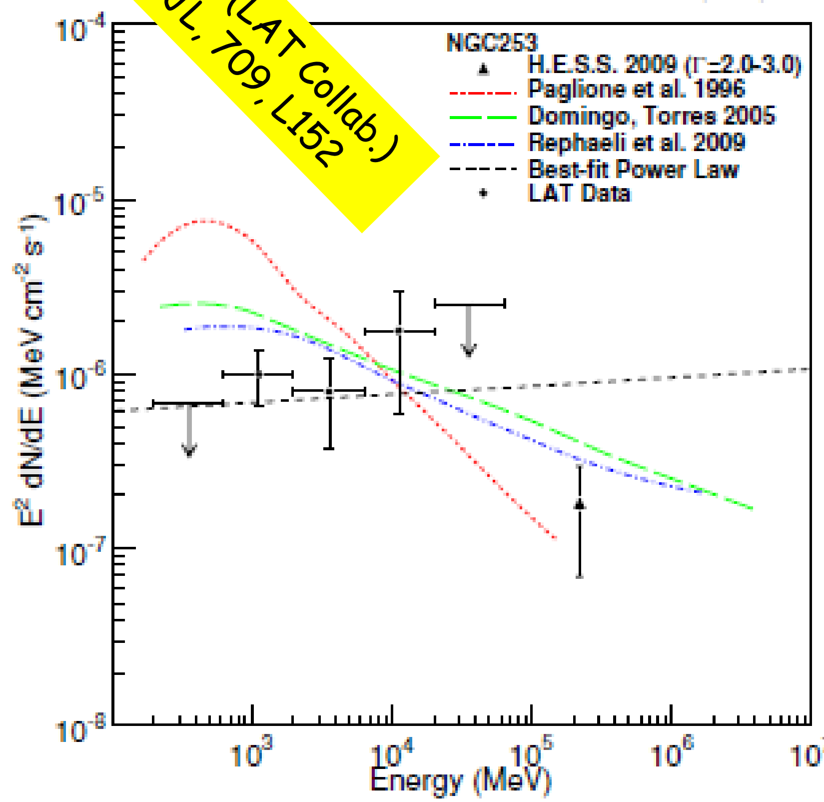
NGC 253 detection





Acero et al. (HESS Collab.) 2009 Science, 326, 1080

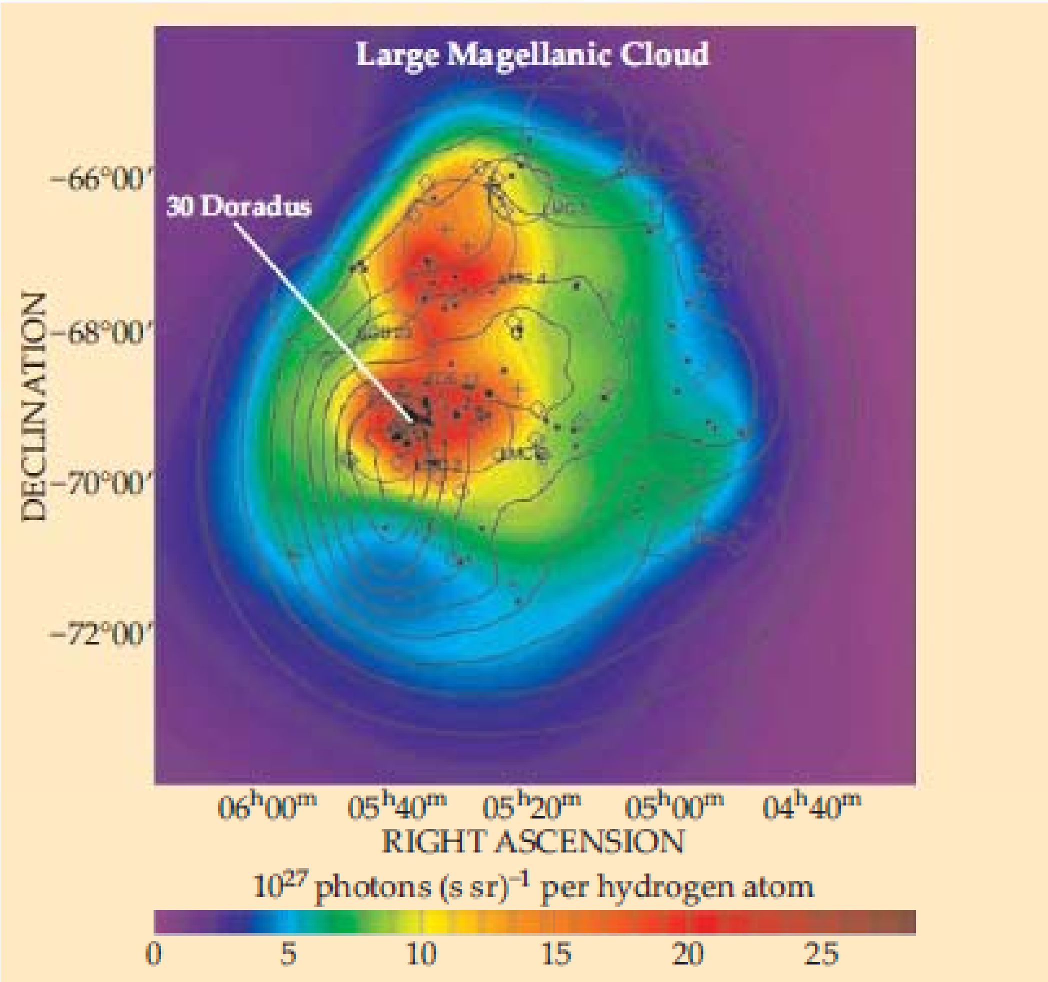




Abdo et al. (LAT Collab.) 2010, ApJL, 709, L152

Large Magellanic Cloud (LMC)

Abdo et al. (LAT Collab.) 2010, A&A, 512, 7



$U_p \sim 0.2\text{-}0.3$ eV cm^{-3}

$M_H \sim 7 \times 10^8 M_\otimes$

Cosmic rays in SF'ing galaxies

CR – SN relation (Ginzburg & Syrovatskii 1964)

- Fermi-I mechanism → SNRs
- SN rates, massive star formation

Test:

γ-ray (direct)

$$U_p \sim ¼ \; (\nu_{SN}\, \tau_{-}) \; (\eta\, E_{ej}) \; r_s^{-3}$$

radio (indirect)
→ field- particles equipartition

observed

Milky Way normalization

observed

- NT synchrotron (radio)

$\chi \approx 1.5$

$$N_e(\gamma) = N_{e,0}\,(1+\chi)\,\gamma^{-q}$$

$$f_\nu = 5.67 \times 10^{-22}\,\frac{r_s^3}{d^2} N_{e,0}(1+\chi)\;a(q)\;B^{\frac{q+1}{2}} \times \left(\frac{\nu}{4\times 10^6}\right)^{-\frac{q-1}{2}} \quad \mathrm{erg/(s\ cm^2 Hz)}$$

$$B_{eq} = \left[\frac{7.44\times 10^{-21}}{1+\chi}\left[1+\frac{\kappa(q)}{1+\chi}\right]\frac{\gamma_1^{2-q}\,250^{q/2}\,\psi}{(q-2)\,a(q)}\right]^{\frac{2}{5+q}}$$

$$U_p\left[1+\frac{1}{\kappa_\chi(q)}\right] \simeq \frac{B^2}{8\pi}$$

- π^0 decay (γ-rays)

NGC 253	→	$U_p \approx$	**125 eV cm^{-3}**
M 82	→		**111**
Arp 220	→		**476**
Milky Way	→		**1**

NGC 253	→	$U_p \approx$	125 eV cm^{-3}
M 82	→		111
Arp 220	→		476
Milky Way	→		1

MP & YR 2010 MNRAS 403, 1569

$$U_p \sim \tfrac{1}{4}\ (\nu_{SN}\ \tau_-)\ (\eta\ E_{ej})\ r_s^{-3}$$

SN rate — obs'd

particle accel. eff. — $\eta \approx 5\%$

SB radius — obs'd

protons' lifetime

kin. energy of SN ejecta — $E_{ej} \approx 10^{51}$ erg

$\tau_- \approx$

- $(\sigma_{pp}\, c n_p)^{-1} \sim 2 \times 10^7\, n_p^{-1}$ yr — hadronic
- $\sim 3 \times 10^4\ (r_s/0.3\ \mathrm{kpc})\ (v_{out}/2500\ \mathrm{km\ s^{-1}})^{-1}$ yr — advection

$$\Rightarrow\ U_p = 85\ \frac{\nu_{SN}}{0.3\,\mathrm{yr}^{-1}}\ \frac{\tau_-}{3\times 10^4\,\mathrm{yr}}\ \frac{\eta}{0.05}\ \frac{E_{ej}}{10^{51}\,\mathrm{erg}}\ \left(\frac{r_s}{0.3\,\mathrm{kpc}}\right)^{-3}\ \mathrm{eV\ cm^{-3}}$$

ν_{SN}		r_s
$0.1-0.2)\ \mathrm{yr}^{-1}$	NGC 253	0.20 kpc
$0.2-0.3)\ \mathrm{yr}^{-1}$	M 82	0.26 kpc
$4 \pm 2)\ \mathrm{yr}^{-1}$	Arp 220	0.25 kpc

From SN statistics → $U_p \sim O(100\ \mathrm{eV})$ in starbursts
$U_p \sim O(1\ \mathrm{eV})$ in Galaxy

Insights on the stellar IMF ?

MP & YR 2010
MNRAS, 403, 1569

$$\nu_{SN} \equiv \frac{dN_{SN}}{dt} = \mathrm{SFR}\ \frac{\int_{8M_\odot}^{M_{up}} m^{-x}\,dm}{\int_{M_{low}}^{M_{up}} m^{-x+1}\,dm}$$

$$\mathrm{SFR} = \frac{L_{TIR}}{2.2\times10^{43}\ \mathrm{erg}}\quad M_\odot\,\mathrm{yr}^{-1}$$

(Kennicutt 1998)

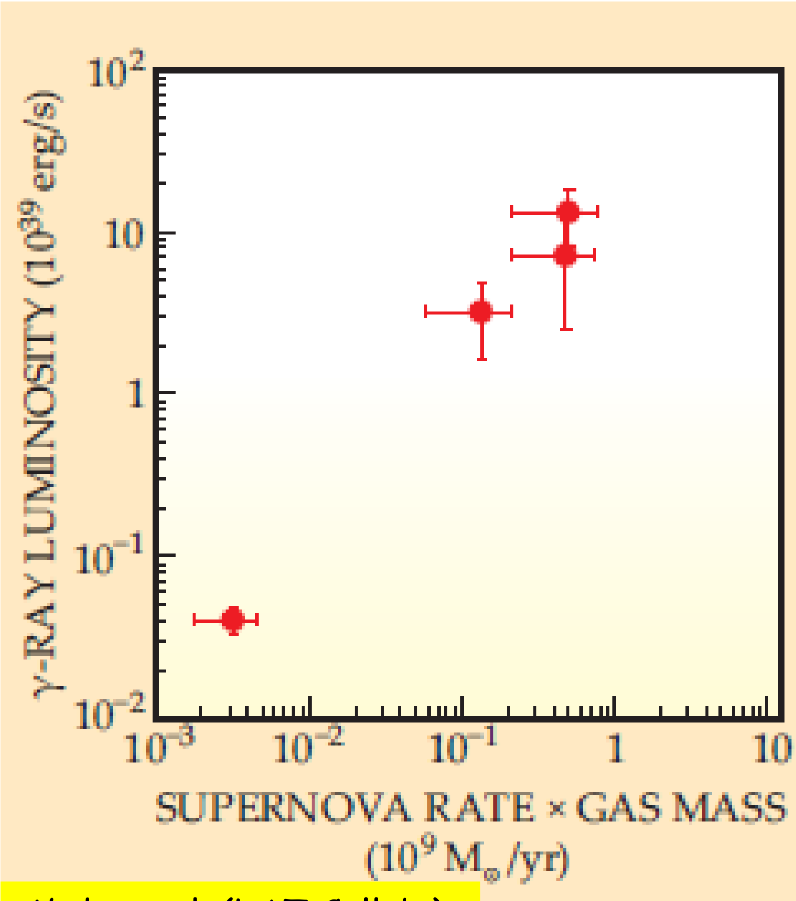
stellar IMF:
$x=2.35$, $M_{up}=100\ M_\odot$, $M_{low}=0.1M_\odot$
(Salpeter 1955)

$$M_{low} = 2\,M_\odot \quad \nu_{SN} = \begin{cases} 0.12\,\mathrm{yr}^{-1} \\ 0.26\,\mathrm{yr}^{-1} \\ 5.6\,\mathrm{yr}^{-1} \end{cases}$$

NGC 253 $(0.1-0.2)\,\mathrm{yr}^{-1}$
M 82 $(0.2-0.3)\,\mathrm{yr}^{-1}$
Arp 220 $(4\pm2)\,\mathrm{yr}^{-1}$

$$M_{low} \sim 0.1\,M_\odot \qquad \nu_{SN} \sim 0.015\,\mathrm{yr}^{-1}$$

Galaxy $(0.02\pm0.01)\,\mathrm{yr}^{-1}$



Abdo et al. (LAT Collab.)
2010, ApJL, 709, L152

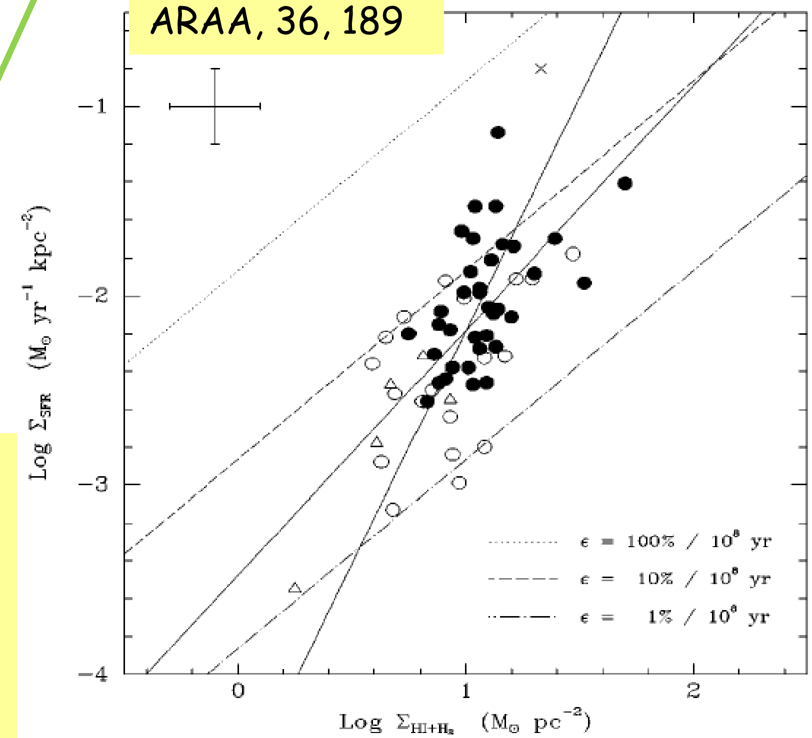
$$L(\geq \epsilon) = \int_V g(\geq \epsilon)\, n\, U_p\, dV \quad s^{-1}$$

$\propto \nu_{SN}$

~ const, galaxy-wide

M_H

Kennicutt 1998
ARAA, 36, 189



Schmidt law: SFR $\propto M_H^x$
x~ 2.4 (Kennicutt 1998)
→$L_\gamma \propto \nu_{SN}\, M_H \propto$
SFR $M_H \propto$
$SFR^{1+1/x}$ = $\mathbf{SFR^{1.4}}$

Conclusion

In SF'ing galaxies:

Astroparticles

Strong CR production

universal acceleration efficiency of SN

particles/field equipartition

U_p from radio ok → good for high-z gal's

Astrophysics

NT emission

synchrotron radio emission

π^0 γ-ray (GeV-TeV) emission

IMF top-heavy ($M_{low} \sim 2\, M_\odot$) ?

higher T, σ_v → higher Jeans mass

Cosmology

Top-heavy IMF in all early SF galaxies?

renormalize SFR(z)?

fraction of cosmic γ-ray bkgd tracer of cosmic SF (cf EBL)