γ-rays from Starburst Galaxies: CRs in External Galaxies

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Starburst galaxies

Star formation → SN explosions → CRs (Ginzburg & Syrovatskii 1964)

EM consequence: *e* synchrotron → **radio**

e bremss, *e* IC, π^0 decay → **γ**

Info on CR from their radiative yield: γ-rays

radio

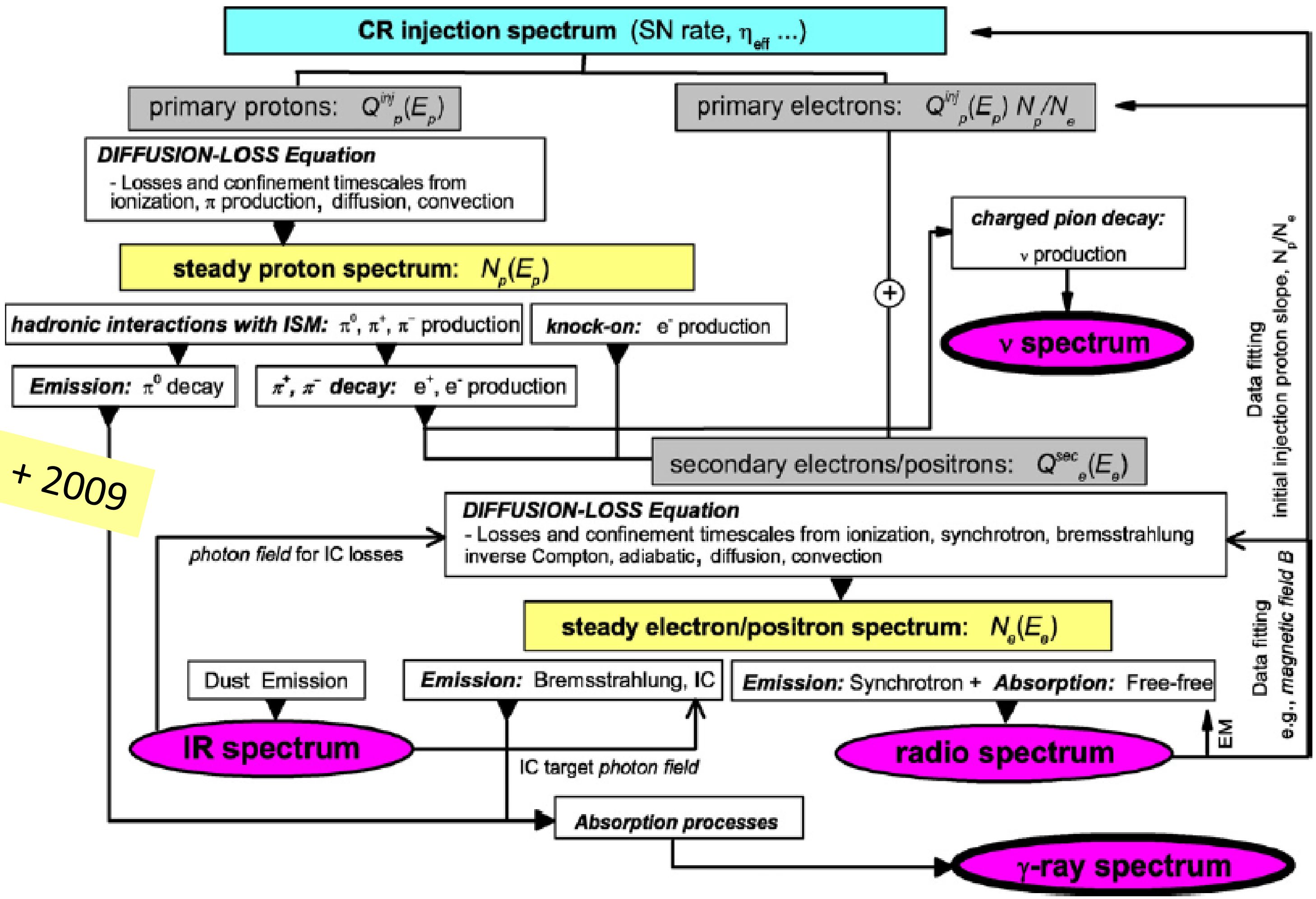
« « star formation: SN rates

Model SED → CR properties

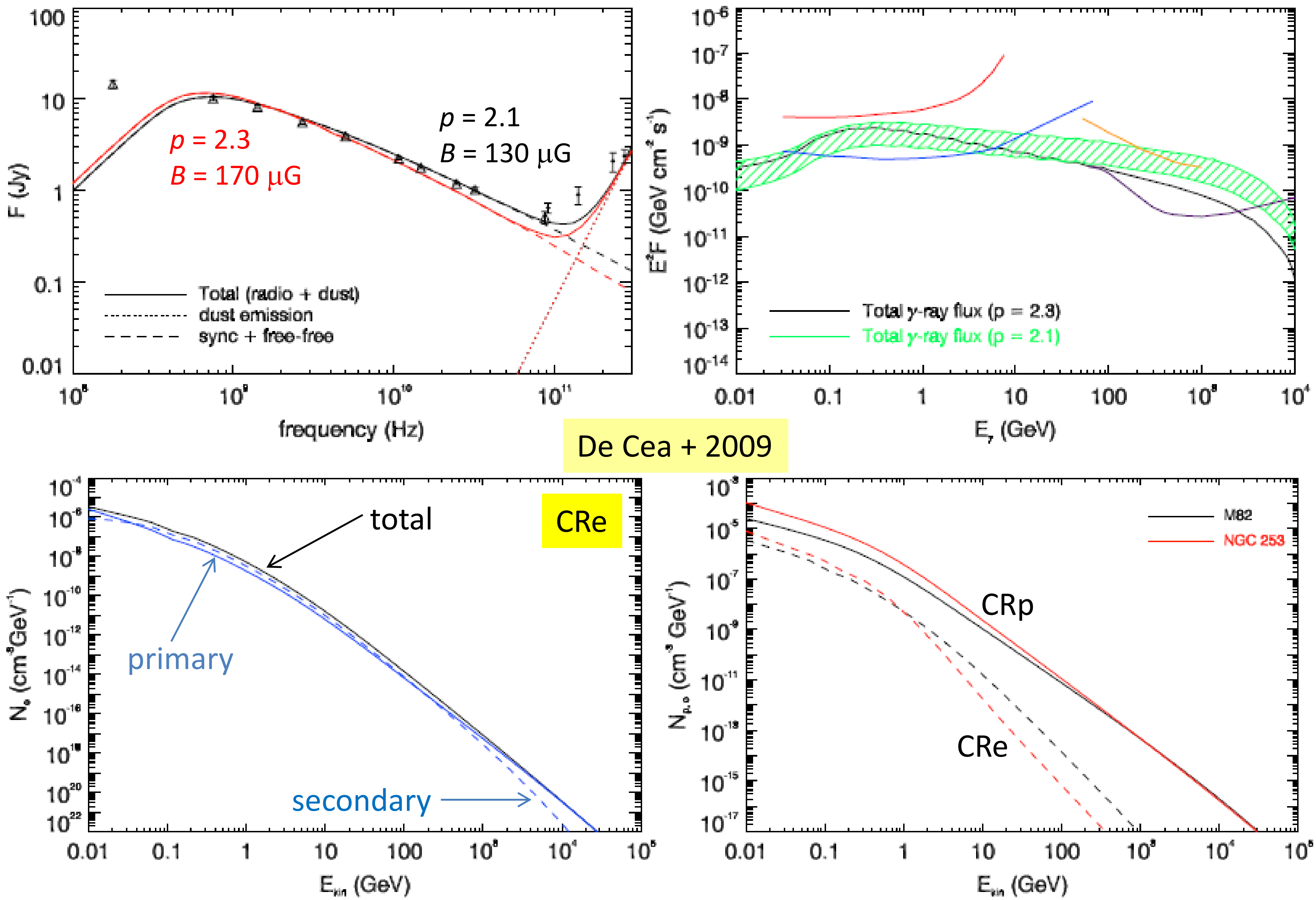
diffusion-loss equation for CRs

$$\frac{\partial N(E)}{\partial t} = D\nabla^2 N(E) - \frac{N(E)}{\tau(E)} + \frac{\mathrm{d}}{\mathrm{d}E}[b(E)N(E)] + Q(E)$$

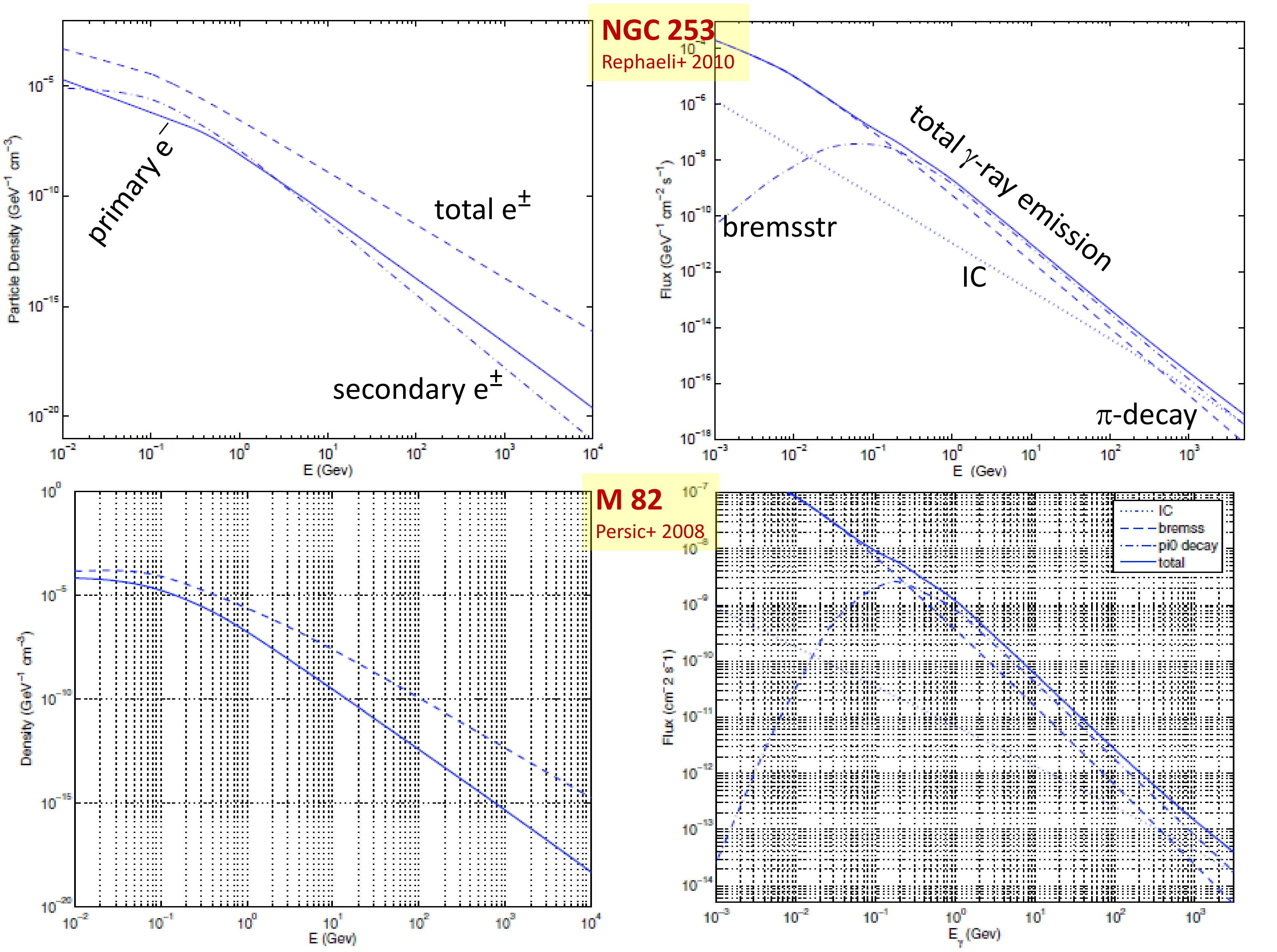
diffusion | residency | loss | source



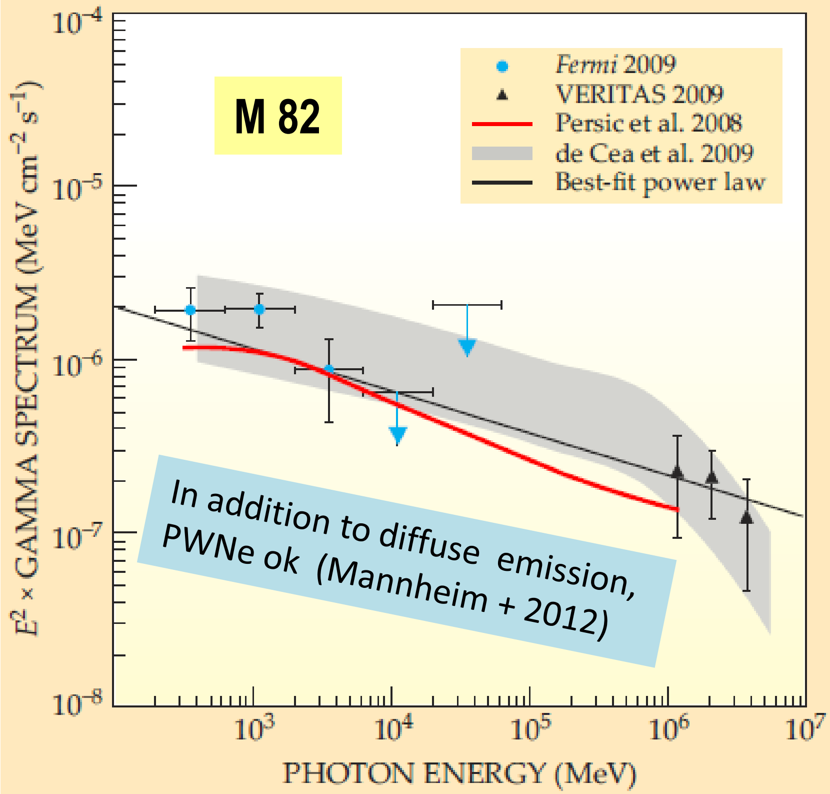
De Cea + 2009



F (Jy)
frequency (Hz)
p = 2.3
B = 170 μG
p = 2.1
B = 130 μG
Total (radio + dust)
dust emission
sync + free-free
E²F (GeV cm⁻² s⁻¹)
Eγ (GeV)
Total γ-ray flux (p = 2.3)
Total γ-ray flux (p = 2.1)
De Cea + 2009
Ne (cm⁻³GeV⁻¹)
Ekin (GeV)
total
CRe
primary
secondary
Np,e (cm⁻³ GeV⁻¹)
M82
NGC 253
CRp
CRe



NGC 253
Rephaeli+ 2010
primary e⁻
total e±
secondary e±
Particle Density (GeV⁻¹ cm⁻³)
E (Gev)
total γ-ray emission
bremsstr
IC
π-decay
Flux (GeV⁻¹ cm⁻² s⁻¹)
E (Gev)
M 82
Persic+ 2008
Density (GeV⁻¹ cm⁻³)
E (Gev)
IC
bremss
pi0 decay
total
Flux (cm^-2 s^-1)
Eγ (Gev)



Physics Today
January 2010

Paglione+ 1996
Persic + 2008
De Cea + 2009
Rephaeli + 2010

→

U_p ~ 230 eV cm^{-3}
U_e ~ 20 eV cm^{-3}
B ~ 100 μG

in SB nuclei
ν_{SN} ~ 0.2 -1 yr^{-1}

vs.

U_p ~ 1 eV cm^{-3}
U_e ~ 0.2 eV cm^{-3}
B ~ 5 μG

in MW @ Earth
ν_{SN} ~ 0.02 yr^{-1}

Radio emission → CRe → CRp

$$B_{\rm eq} = \left[\frac{7.44\times10^{-21}}{1+\chi}\left[1+\frac{\kappa(q)}{1+\chi}\right]\frac{\gamma_1^{2-q}\,250^{q/2}\,\psi}{(q-2)\,a(q)}\right]^{\frac{2}{5+q}}$$

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

- $U_{\rm e} = N_{e,0}\,(1+\chi)\,m_{\rm e}c^2\,\gamma_1^{2-q_{\rm e}}\,\frac{[1-(\gamma_2/\gamma_1)^{2-q_{\rm e}}]}{(q_{\rm e}-2)}$

$$N_{\rm e,0}(1+\chi) = 1.6\times10^{-16}\,a_{q_{\rm e}}^{-1}\,\psi_5\,1250^{\frac{q_{\rm e}}{2}}\,B^{-\frac{q_{\rm e}+1}{2}}$$

$$\psi_5 \equiv \left(\frac{r_{\rm s}}{0.1\,{\rm kpc}}\right)^{-3}\left(\frac{d}{\rm Mpc}\right)^2\left(\frac{f_5}{\rm Jy}\right)$$

- $U_{\rm e} = 1.3\times10^{-22}\,1250^{\frac{q_{\rm e}}{2}}\,\psi_5 B^{-\frac{q_{\rm e}+1}{2}}\,\frac{\gamma_1^{2-q_{\rm e}}[1-(\gamma_2/\gamma_1)^{2-q_{\rm e}}]}{(q_{\rm e}-2)\,a_{q_{\rm e}}}\,{\rm erg\,cm^{-3}}$

$$\frac{B^2}{8\pi} = \eta\,(U_{\rm p}+U_{\rm e})$$

$$U_{\rm p} \simeq \kappa(q_{\rm p},q_{\rm e})\,\frac{U_{\rm e}}{1+\chi}$$

- $U_{\rm p} = \frac{2.5\times10^{10}}{1\;+\;(1+\chi)/\kappa}\left[3.3\times10^{-21}\left(1+\frac{\kappa}{1+\chi}\right)\gamma_1^{2-q_{\rm e}}\,\frac{[1-(\gamma_2/\gamma_1)^{2-q_{\rm e}}]\,1250^{q_{\rm e}/2}\,\psi_5}{(q_{\rm e}-2)\,a_{q_{\rm e}}}\right]^{4/(5+q_{\rm e})}\;{\rm eV\,cm^{-3}}$

- $B = \sqrt{\eta}\left[3.3\times10^{-21}\left(1+\frac{\kappa}{1+\chi}\right)1250^{q_{\rm e}/2}\,\psi_5 \times\gamma_1^{2-q_{\rm e}}\,\frac{[1-(\gamma_2/\gamma_1)^{2-q_{\rm e}}]}{(q_{\rm e}-2)\,a_{q_{\rm e}}}\right]^{2/(5+q_{\rm e})}\;{\rm G}\,.$

κ = p/e energy density ratio

χ = secondary/primary electron ratio

γ_1 = low energy cutoff

... p/e ratios

... charge neutrality of primary particles

- $$\zeta(T;q) = \begin{cases} 1 & \dots\quad T \ll m_e c^2 \\ \propto \left(\frac{T}{m_p c^2}\right)^{\frac{q-1}{2}} & \dots\quad m_e c^2 \ll T \ll m_p c^2 \\ \left(\frac{m_p}{m_e}\right)^{\frac{q-1}{2}} & \dots\quad T \gg m_p c^2. \end{cases}$$

- $$\kappa(T_0; q_p, q_e) = \frac{(q_p - 1)}{(q_e - 1)} \frac{(T_0^2 + 2T_0 m_p c^2)^{\frac{q_p-1}{2}}}{(T_0^2 + 2T_0 m_e c^2)^{\frac{q_e-1}{2}}} \frac{\int_{T_0}^{\infty} T^{-\frac{q_p-1}{2}} (T + 2m_p c^2)^{-\frac{q_p+1}{2}} (T + m_p c^2)\, \mathrm{d}T}{\int_{T_0}^{\infty} T^{-\frac{q_e-1}{2}} (T + 2m_e c^2)^{-\frac{q_e+1}{2}} (T + m_e c^2)\, \mathrm{d}T}$$

q_p	q_e	κ	q_p	q_e	κ	q_p	q_e	κ	q_p	q_e	κ	q_p	q_e	κ
2.0	2.0	0.258E+02	2.1	2.0	0.984E+01	2.2	2.0	0.418E+01	2.3	2.0	0.197E+01	2.4	2.0	0.101E+01
2.0	2.1	0.628E+02	2.1	2.1	0.239E+02	2.2	2.1	0.102E+02	2.3	2.1	0.479E+01	2.4	2.1	0.246E+01
2.0	2.2	0.119E+03	2.1	2.2	0.453E+02	2.2	2.2	0.193E+02	2.3	2.2	0.906E+01	2.4	2.2	0.466E+01
2.0	2.3	0.189E+03	2.1	2.3	0.720E+02	2.2	2.3	0.306E+02	2.3	2.3	0.144E+02	2.4	2.3	0.740E+01
2.0	2.4	0.269E+03	2.1	2.4	0.102E+03	2.2	2.4	0.436E+02	2.3	2.4	0.205E+02	2.4	2.4	0.105E+02
2.0	2.5	0.357E+03	2.1	2.5	0.136E+03	2.2	2.5	0.578E+02	2.3	2.5	0.272E+02	2.4	2.5	0.140E+02
2.0	2.6	0.451E+03	2.1	2.6	0.172E+03	2.2	2.6	0.731E+02	2.3	2.6	0.344E+02	2.4	2.6	0.177E+02
2.0	2.7	0.551E+03	2.1	2.7	0.210E+03	2.2	2.7	0.892E+02	2.3	2.7	0.420E+02	2.4	2.7	0.216E+02
2.0	2.8	0.654E+03	2.1	2.8	0.249E+03	2.2	2.8	0.106E+03	2.3	2.8	0.499E+02	2.4	2.8	0.256E+02
2.0	2.9	0.760E+03	2.1	2.9	0.289E+03	2.2	2.9	0.123E+03	2.3	2.9	0.579E+02	2.4	2.9	0.298E+02
2.0	3.0	0.867E+03	2.1	3.0	0.330E+03	2.2	3.0	0.140E+03	2.3	3.0	0.661E+02	2.4	3.0	0.340E+02

$q_p = q_e = q$ → $\kappa(q) \simeq \left(\frac{m_p}{m_e}\right)^{(3-q)/2}$

q_p = 2.2
q_e from radio

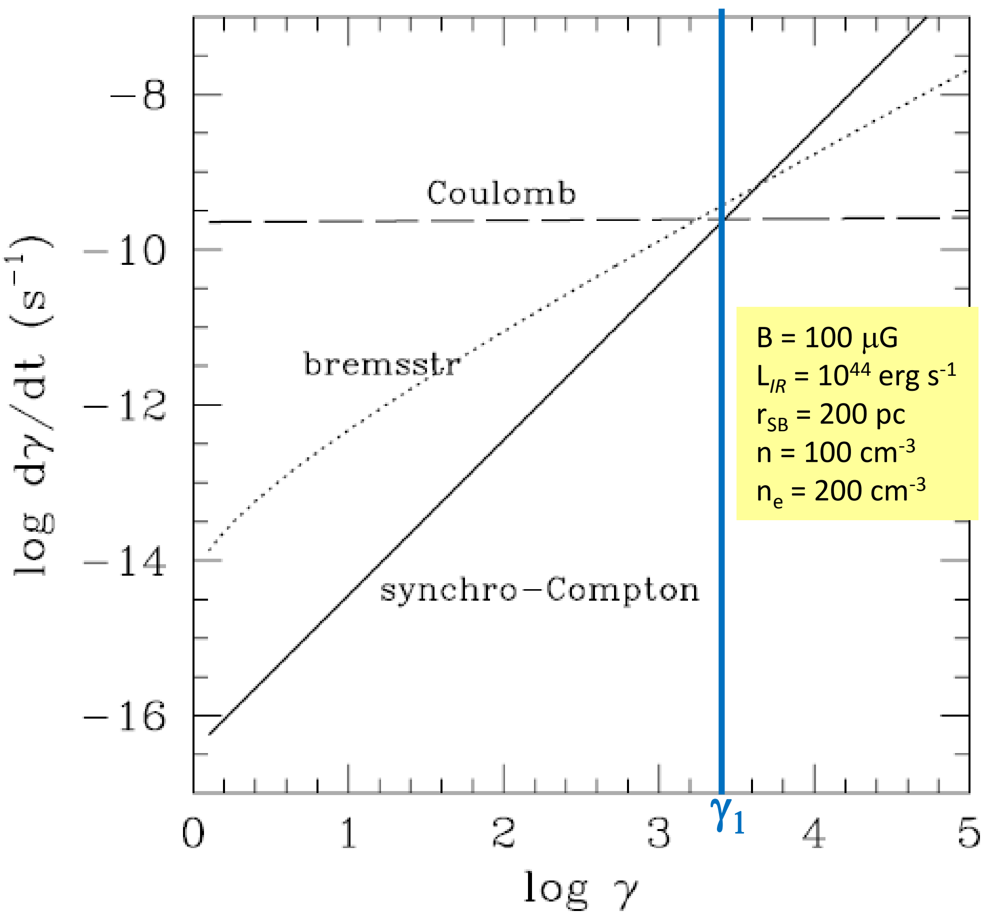
Electron Radiation Losses

→ γ_1

$$b_0 = -\dot{\gamma}_c \simeq 1.2\times 10^{-12}\, n_e \left[1.0 + \frac{\ln(\gamma/n_e)}{84}\right] s^{-1}$$ *Coulomb*

$$b_1 = -\dot{\gamma}_b \simeq \begin{cases} 1.78\times 10^{-16} n\gamma[\ln(\gamma)+0.36]\ s^{-1} & \text{ionized} \\ 9.44\times 10^{-16} n\gamma\ s^{-1} & \text{neutral} \end{cases}$$ bremsstrahlung

$$b_2 = -\dot{\gamma}_{SC} = 1.3\times 10^{-9}\,\gamma^2 (B^2 + 8\pi\rho_{IR})\ s^{-1}$$ synchrotron + Compton



Coulomb losses dominate @ LE
Synchro + Compton « @ HE

Secondary/primary electron ratio

$$\chi = \frac{2}{3}\zeta\sqrt{3}\, r_s\, n\, \sigma_{pp} \sim 0.6\text{–}1$$

$r_s = 0.2\,\mathrm{kpc}$, $n = 200\,\mathrm{cm}^{-3}$, and $q = 2.2$

Object	D_L[1]	R_{SB}[2]	h_{SB}[3]	f_5[4]	α[5]	n_e[6]	L_{IR}[7]	M_{SB}[8]	χ[9]	κ[10]	γ_1[11]	B[12]	U_p[13]	Notes[a]
Arp 220 E	74.7	114$^+$	–	0.08	0.70	3000$^+$	44.91	9.3	24	48	21000	155	390	
Arp 220 W	74.7	70$^+$	–	0.10	0.70	3000$^+$	45.08	9.1	40	48	15000	230	730	
Arp 299-A	43.0	140	200*	0.10	0.60	250	44.88	9.0	8	20	8700	145	365	=IC 694
NGC 253	2.5	180	150	1.80	0.70	100	43.62	7.7	0.3	48	8300	100	235	
NGC 3034	3.4	300	200	3.70	0.71	200	43.96	8.1	0.3	51	6600	100	250	=M 82
NGC 3628	7.6	135	200*	.065	0.86	100	43.30	7.3	0.1	120	7600	65	100	
NGC 4945	3.7	250	200*	2.25	0.60	300	43.72	7.4	0.1	20	4700	110	270	
NGC 5236	3.7	180	200*	0.75	0.80	200	43.45	7.3	0.1	90	5000	105	260	=M 83
NGC 6946	5.5	150	200*	.045	0.74	100	43.51	7.0	0.7	60	4000	65	110	

… however, there is a correction →
PL to curved CRe spectrum →
lower equipartition values

- $N_1 \gamma^{-q_{pl}}$

$$j_{pl}(\nu) = \frac{\sqrt{3} e^3 B N_1}{4\pi m c^2} \int sin(\theta) d\Omega \int_{\gamma_1}^{\gamma_2} \gamma^{-q_{pl}} d\gamma \frac{\nu}{\nu_c} \int_{\nu/\nu_c}^{\infty} K_{5/3}(\xi) d\xi$$

$\nu_c = 3eB/(4\pi mc)\, \gamma^2 \sin(\theta)$

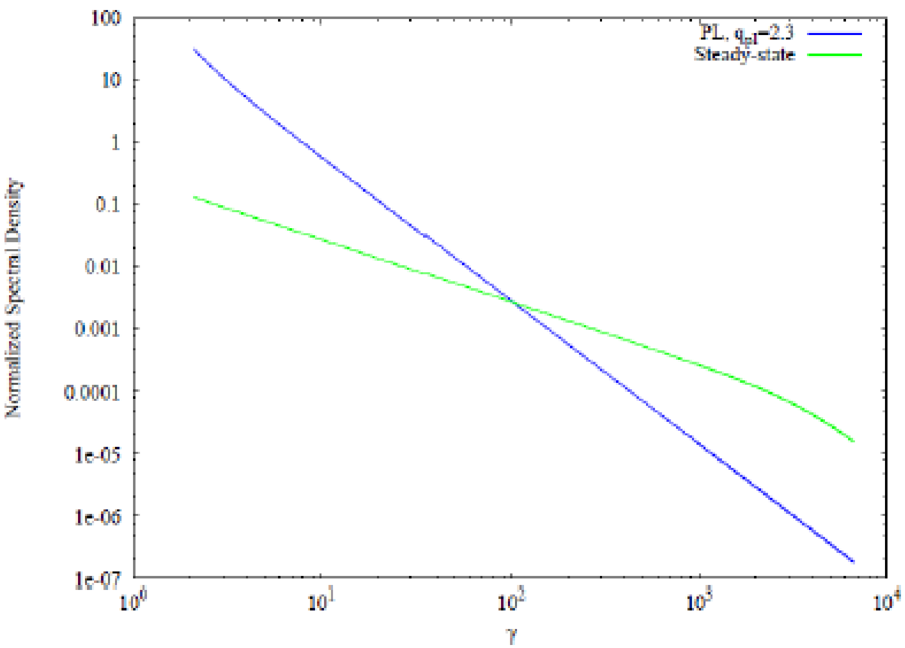
$K_{5/3}(\xi) = \int_0^{\infty} \exp^{-\xi cosh(t)} cosh(5t/3) dt$

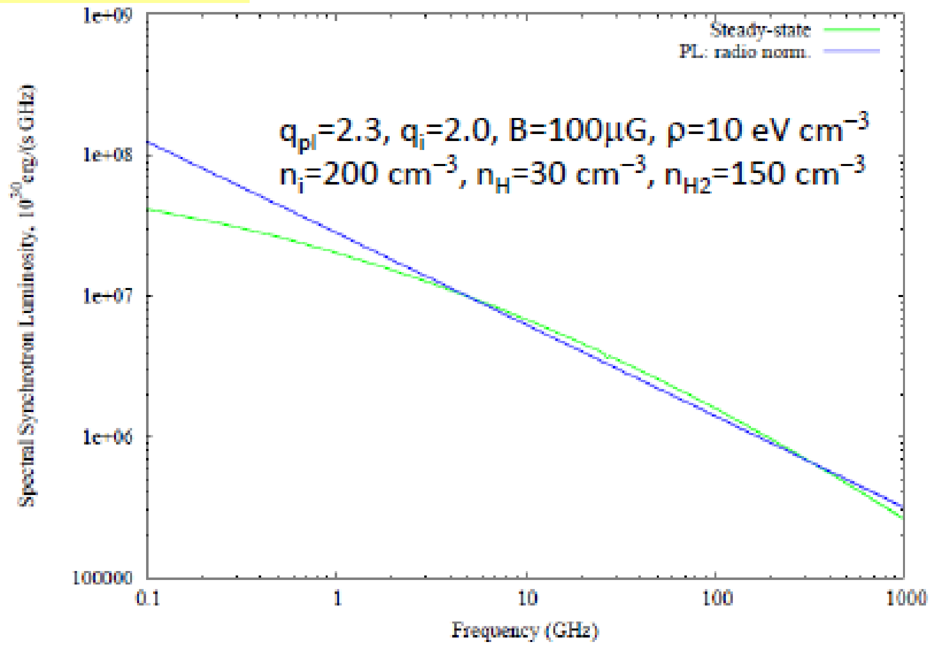
$\nu_c(\gamma_1) \ll \nu \ll \nu_c(\gamma_2) \quad \gamma \in [0, \infty)$

$$j_{pl}(\nu) = \frac{4\pi e^3}{mc^2} a(q_{pl}) N_1 B \left(\frac{\nu_0}{\nu}\right)^{(q_{pl}-1)/2}$$

$$N(\gamma) = \frac{k_i \gamma^{-(q_i - 1)}}{b(\gamma)(q_i - 1)} \qquad j(\nu) = \frac{\sqrt{3} e^3 B k_i}{2mc^2 (q_i - 1)} \int_0^{\pi} sin(\theta) d\theta \int_{\gamma_1}^{\gamma_2} \frac{\gamma^{-(q_i - 1)}}{b(\gamma)} d\gamma \frac{\nu}{\nu_c} \int_{\nu/\nu_c}^{\infty} K_{5/3}(\xi) d\xi$$

Persic & Rephaeli 2015





→ B can be lower by ≤2, U_{CR} by ≤4 than in PL case

SN rate → CRp

$$\tau_{\rm pp} \sim 2\times10^5 \left(\frac{n_{\rm p}}{100\,{\rm cm^{-3}}}\right)^{-1} {\rm yr}$$

$$\tau_{\rm out} = 3\times10^4 \left(\frac{r_{\rm s}}{0.3\,{\rm kpc}}\right)\left(\frac{v_{\rm out}}{2500\,{\rm km\,s^{-1}}}\right)^{-1} {\rm yr}$$

$$\tau_{\rm res}^{-1} = \tau_{\rm pp}^{-1}(n_{\rm HI}) + \tau_{\rm out}^{-1}(r_{\rm s}, v_{\rm out})$$

$$U_{\rm p} = 85 \frac{\nu_{\rm SN}}{0.3\,{\rm yr^{-1}}} \frac{\tau_{\rm res}}{3\times10^4\,{\rm yr}} \frac{\eta}{0.05} \frac{E_{\rm ej}}{10^{51}\,{\rm erg}} \left(\frac{r_{\rm s}}{0.3\,{\rm kpc}}\right)^{-3} {\rm eV\ cm^{-3}}$$

Object	D_L[1] (Mpc)	r_s[2] (kpc)	$f_{1\,\rm GHz}$[3] (Jy)	$\alpha_{\rm NT}$[4]	$n_{\rm e,\,th}$[5] ($\rm cm^{-3}$)	$L_{\rm TIR}$[6] (erg/s)	SFR[7] ($M_\odot$/yr)	$\nu_{\rm SN}$[8] ($\rm yr^{-1}$)	$M_{\rm gas}$[9] ($M_\odot$)	L_γ[10] (erg/s)	$\tau_{\rm res}$[11] (yr)	Notes
Arp 220	74.7	0.25	0.3	0.65	300	45.75	253	3.5	$9.24^{+0.10}_{-0.11}$	< 42.25	9.0E+3	SB
M 82	3.4	0.26	10.0	0.71	200	44.26	8.2	0.25	$9.37^{+0.09}_{-0.14}$	$40.21^{+0.10}_{-0.13}$	2.6E+3	SB
NGC 253	2.5	0.20	5.6	0.75	400	44.23	7.7	0.12	$9.20^{+0.10}_{-0.11}$	$39.76^{+0.14}_{-0.19}$	2.0E+4	SB
Milky Way	–	4.4	–	–	0.01	43.75	2.5	0.02	$9.81^{+0.12}_{-0.16}$	$38.91^{+0.12}_{-0.15}$	2.7E+7	quiescent
M 31	0.78	5.17	4.8	0.88	0.01	42.98	0.43	0.01	$9.88^{+0.11}_{-0.15}$	$38.66^{+0.09}_{-0.10}$	4.0E+7	quiescent
M 33	0.85	2.79	3.30	0.95	0.03	42.68	0.22	0.003	$9.35^{+0.13}_{-0.19}$	< 38.54	2.6E+7	quiescent
LMC	0.049	3.0	285.0	0.84	0.01	42.45	0.16	0.002	$8.86^{+0.12}_{-0.18}$	$37.67^{+0.05}_{-0.05}$	1.0E+7	quiescent
SMC	0.061	1.53	45.3	0.85	0.01	41.45	0.01	0.001	$8.66^{+0.03}_{-0.06}$	$37.04^{+0.11}_{-0.14}$	4.0E+7	quiescent
NGC 4945	3.7	0.22	5.5	0.57	300	44.02	4.7	0.1-0.5	$9.64^{+0.10}_{-0.40}$	$40.30^{+0.12}_{-0.16}$	4.6E+4	SB+Sy2
NGC 1068	16.7	1.18	6.6	0.75	300	45.05	50	0.2-0.4	$9.71^{+0.11}_{-0.19}$	$41.32^{+0.15}_{-0.23}$	1.0E+6	SB+Sy2

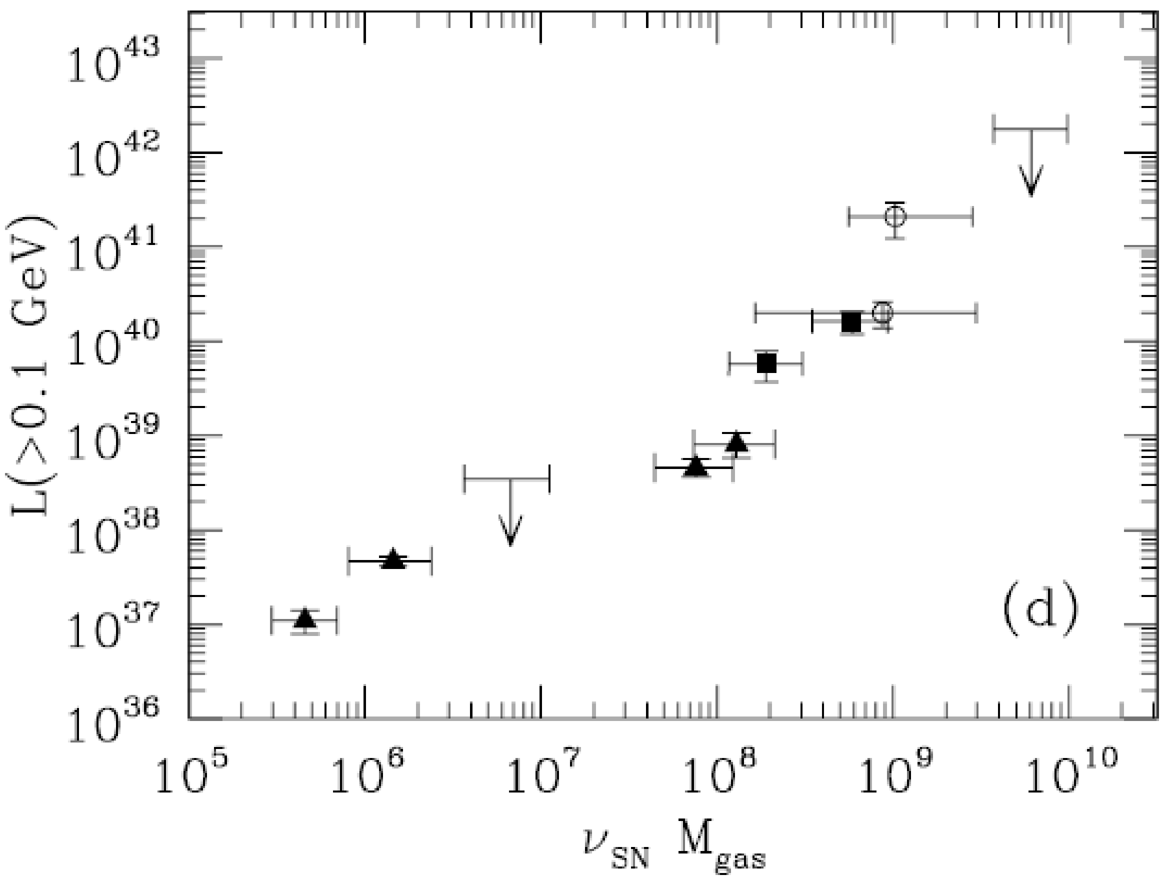
Object	γ-ray meth.	radio meth.	SN meth.	other meth.	r_s (kpc)	loss mode
Arp 220	–	1027	515	–	0.25	adv
M 82	200[a,c]	201	95	–	0.26	adv
NGC 253	200[b,c]	145	77	–	0.20	adv
Milky Way	1[d]	–	1	1[j]	4.4	pp
	6[e]	–	5	–	0.2	pp
M 31	0.36[f]	0.15	0.7	–	4.77	pp
M 33	< 3[f]	0.38	0.7	–	2.79	pp
LMC	0.25[g]	0.14	0.2	–	3.0	pp
SMC	0.15[h]	0.39	1.0	–	1.53	pp
NGC 4945	200[i]	201	220	–	0.22	adv
NGC 1068	–	65	61	–	1.18	pp

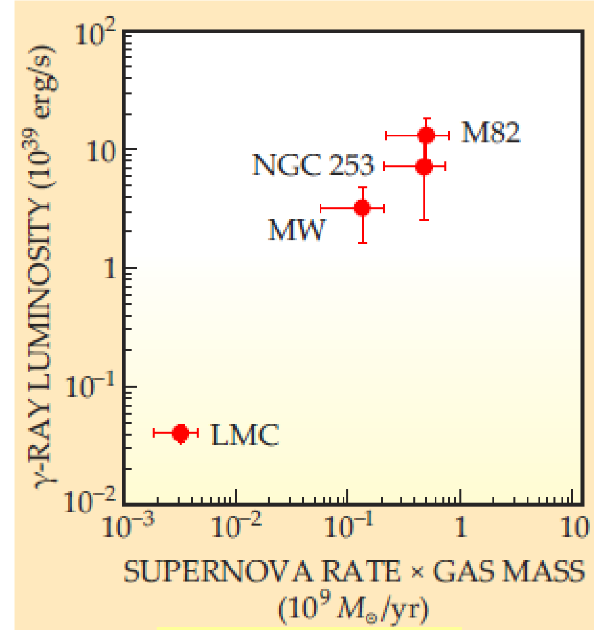
pionic channel

$$L_{\geq E}^{[q]} = \int_V g_{\geq E}^{[q]} \, n_{\rm gas} \, U_{\rm p} \, {\rm d}V \; {\rm s}^{-1} \quad \propto \nu_{\rm SN} \, M_{\rm gas}$$

$g_{\geq E}^{[q]}$ → ~ const

$n_{\rm gas}$, ${\rm d}V$ → $M_{\rm gas}$





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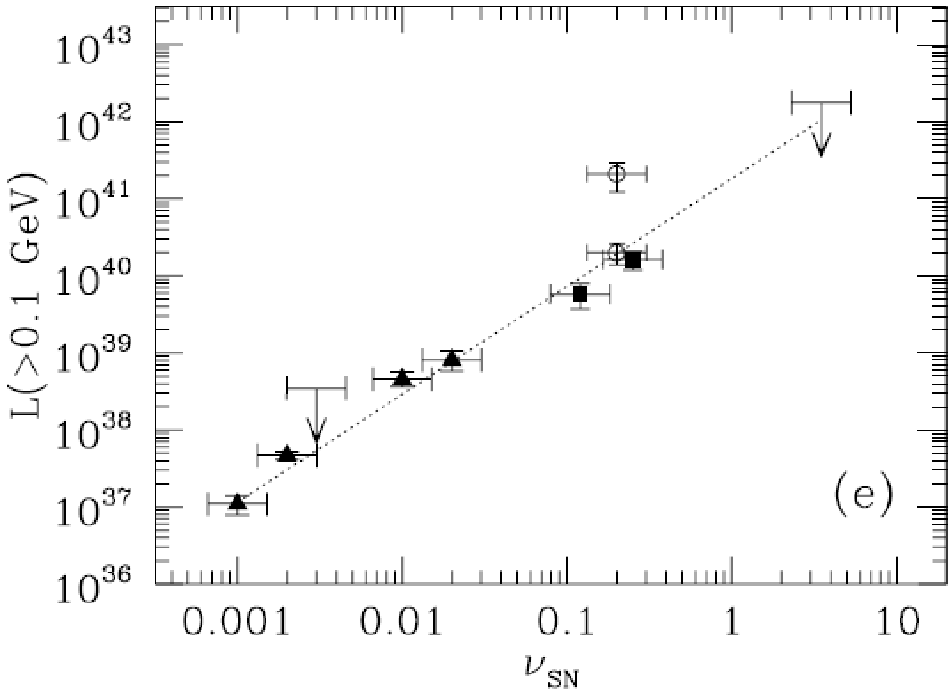
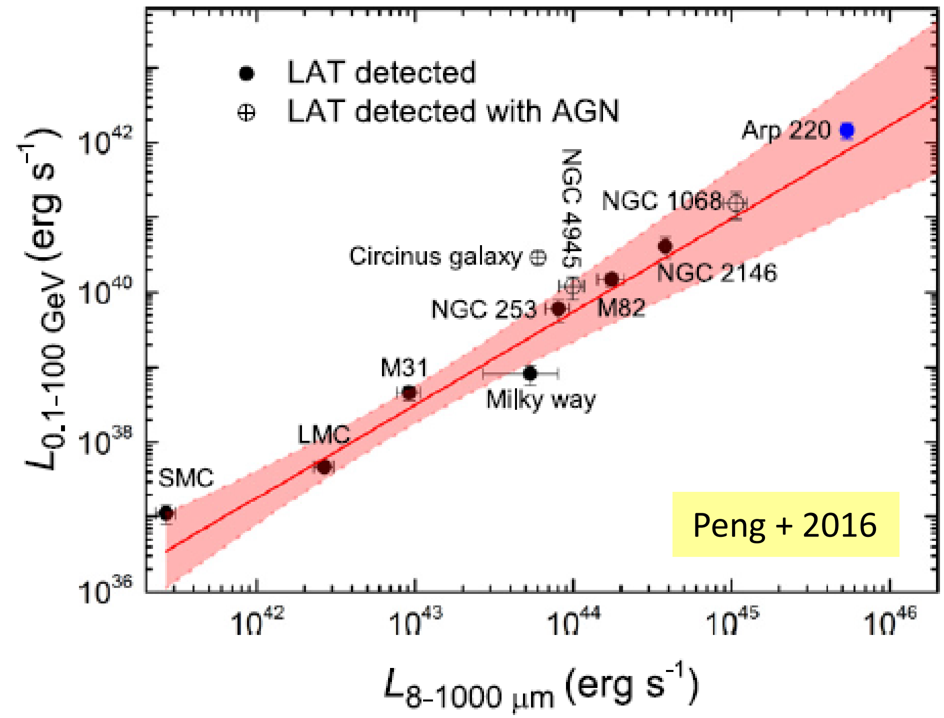
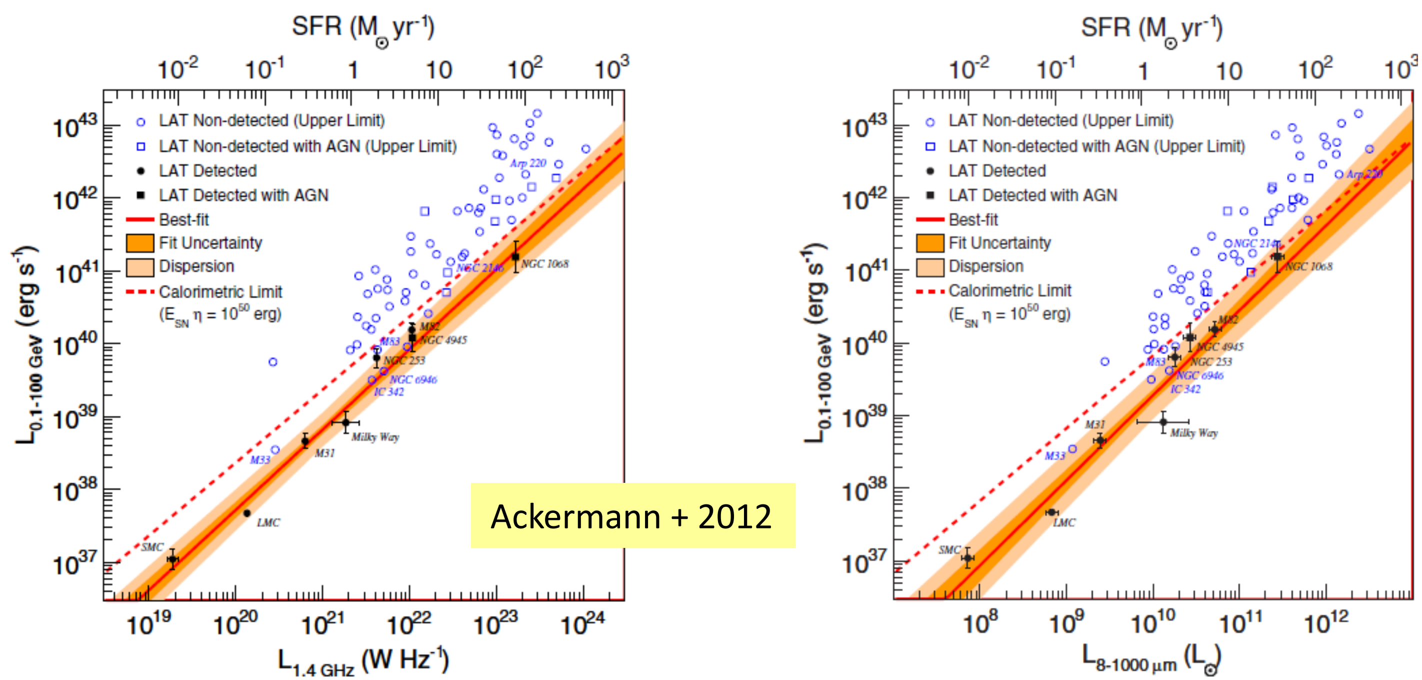
… SFR depends on gas density →


L(>0.1 GeV)
10^{36} 10^{37} 10^{38} 10^{39} 10^{40} 10^{41} 10^{42} 10^{43}
0.001 0.01 0.1 1 10
ν_{SN}
(e)


LAT detected
LAT detected with AGN
Arp 220
NGC 1068
NGC 4945
Circinus galaxy
NGC 2146
NGC 253
M82
M31
Milky way
LMC
SMC
Peng + 2016
$L_{0.1\text{-}100\ \mathrm{GeV}}$ (erg s^{-1})
10^{36} 10^{38} 10^{40} 10^{42}
10^{42} 10^{43} 10^{44} 10^{45} 10^{46}
$L_{8\text{-}1000\ \mu\mathrm{m}}$ (erg s^{-1})


SFR ($M_\odot$ yr^{-1})
10^{-2} 10^{-1} 1 10 10^{2} 10^{3}
LAT Non-detected (Upper Limit)
LAT Non-detected with AGN (Upper Limit)
LAT Detected
LAT Detected with AGN
Best-fit
Fit Uncertainty
Dispersion
Calorimetric Limit
(E_{SN} η = 10^{50} erg)
$L_{0.1\text{-}100\ \mathrm{GeV}}$ (erg s^{-1})
10^{37} 10^{38} 10^{39} 10^{40} 10^{41} 10^{42} 10^{43}
10^{19} 10^{20} 10^{21} 10^{22} 10^{23} 10^{24}
$L_{1.4\ \mathrm{GHz}}$ (W Hz^{-1})
Ackermann + 2012
SFR ($M_\odot$ yr^{-1})
10^{-2} 10^{-1} 1 10 10^{2} 10^{3}
LAT Non-detected (Upper Limit)
LAT Non-detected with AGN (Upper Limit)
LAT Detected
LAT Detected with AGN
Best-fit
Fit Uncertainty
Dispersion
Calorimetric Limit
(E_{SN} η = 10^{50} erg)
$L_{0.1\text{-}100\ \mathrm{GeV}}$ (erg s^{-1})
10^{37} 10^{38} 10^{39} 10^{40} 10^{41} 10^{42} 10^{43}
10^{8} 10^{9} 10^{10} 10^{11} 10^{12}
$L_{8\text{-}1000\ \mu\mathrm{m}}$ ($L_\odot$)

Conclusion

SFGs : correlation between SFR (SN rate) and U_{CB}

High SFR → high U_{CR}

M82, NGC 253: $U_{CR} = O(100)$ eV cm^{-3}
MW, M31, M33: $U_{CR} = O(1)$ eV cm^{-3}
LMC, SMC: $U_{CR} = O(0.1)$ eV cm^{-3}

Nearby gals: estimate U_{CR} from SED →
solve loss-diffusion eqn (w. assumptions).

Distant gals: estimate U_{CR} from electrons →
radio synchrotron + p/e energy density ratio.

SFGs *not* proton calorimeters → CRp (unlike CRe) escape unscathed

L_γ is SFR indicator (like radio, IR)