Cosmic rays in galaxies

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CR – SN relation (Ginzburg & Syrovatskii 1964)

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

Test:

γ-ray (direct)

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

observed

Milky Way normalization

observed

radio (indirect)
→ field- particles equipartition

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

$\chi \approx 1.5$

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

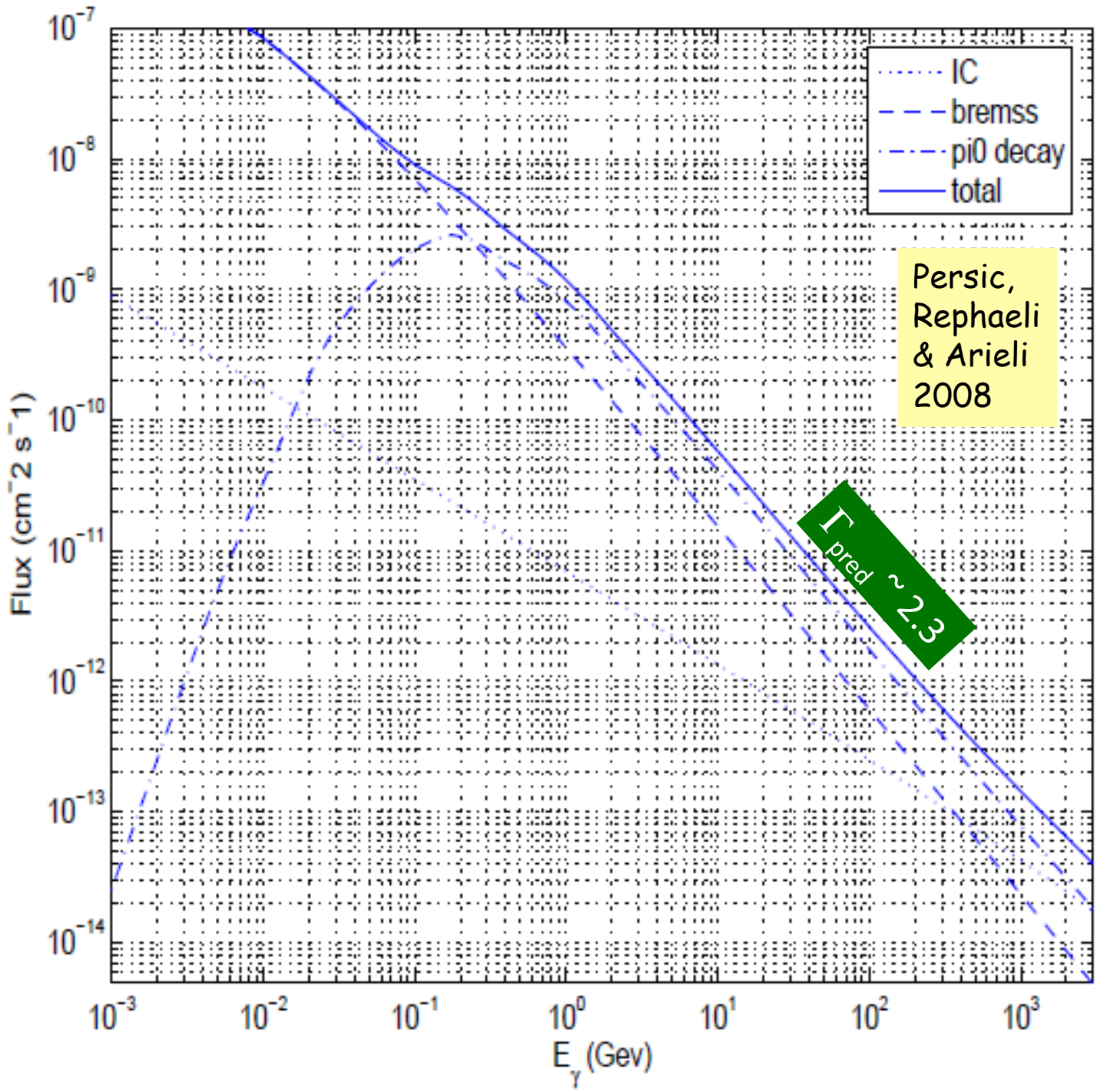
synchrotron radio emission

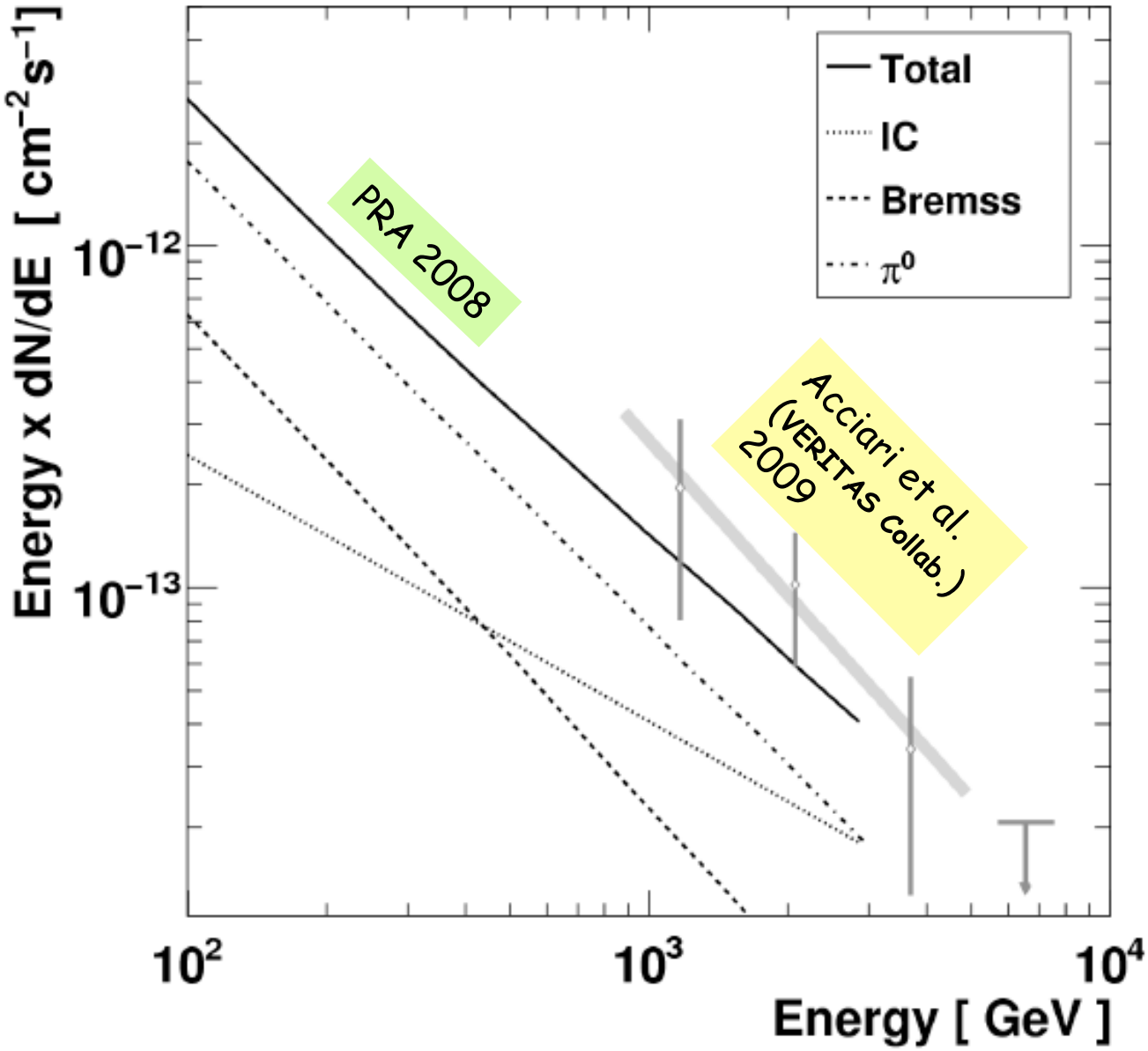
$$B_{eq} = \left[\frac{7.44\times 10^{-21}}{1+\chi}\left[1+\frac{\kappa(q)}{1+\chi}\right]\frac{\gamma_1^{2-q}\,250^{q/2}\,\psi}{(q-2)\,a(q)}\right]^{\frac{2}{5+q}}$$

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

Object	$d^{(a)}$	$f^{(b)}_{12\mu}$	$f^{(b)}_{25\mu}$	$f^{(b)}_{60\mu}$	$f^{(b)}_{100\mu}$	$L^{(c)}_{TIR}$
NGC 253	3.0	41.04	154.67	967.81	1288.15	44.00
M 82	3.6	79.43	332.63	1480.42	1373.69	44.35
Arp 220	72.3	0.61	8.00	104.0	112.0	45.68

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


IC
bremss
pi0 decay
total
Persic, Rephaeli & Arieli 2008
$\Gamma_{pred} \sim 2.3$
Flux (cm^-2 s^-1)
E_γ (Gev)



Fermi LAT discovery, too !

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

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

SN rate — obs'd

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

SB radius — obs'd

electrons' lifetime

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

τ [illegible] $\approx$

$(\sigma_{pp}\, c n_p)^{-1} \sim 2 \times 10^7\, n_p^{-1}$ yr — hadronic

$\sim 3 \times 10^4\ (r_s/0.3\ \mathrm{kpc})\ (v_{out}/2500\ \mathrm{km\ s^{-1}})^{-1}$ yr — advection

$$U_p = 85\ \frac{\nu_{SN}}{0.3\,\mathrm{yr}^{-1}}\ \frac{\tau_-}{3\times10^4\,\mathrm{yr}}\ \frac{\eta}{0.05}\ \frac{E_{ej}}{10^{51}\,\mathrm{erg}}\ \left(\frac{r_s}{0.3\,\mathrm{kpc}}\right)^{-3}\ \mathrm{eV\ cm^{-3}}$$

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
$(4\pm2)\,\mathrm{yr}^{-1}$	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

OK !

Insights on the stellar IMF ?

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

$$\mathrm{SFR} = \frac{L_{\mathrm{TIR}}}{2.2 \times 10^{43}\ \mathrm{erg}}\ M_\odot\,\mathrm{yr}^{-1}$$

(Kennicutt 1998)

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

$$M_{\mathrm{low}} = 2\,M_\odot \quad \nu_{\mathrm{SN}} = \begin{cases} 0.12\,\mathrm{yr}^{-1} & \text{NGC 253} \quad (0.1-0.2)\,\mathrm{yr}^{-1} \\ 0.26\,\mathrm{yr}^{-1} & \text{M 82} \quad (0.2-0.3)\,\mathrm{yr}^{-1} \\ 5.6\,\mathrm{yr}^{-1} & \text{Arp 220} \quad (4 \pm 2)\,\mathrm{yr}^{-1} \end{cases}$$

$$M_{\mathrm{low}} \sim 0.1\,M_\odot \qquad \nu_{\mathrm{SN}} \sim 0.015\,\mathrm{yr}^{-1} \qquad \text{Galaxy} \quad (0.02 \pm 0.01)\,\mathrm{yr}^{-1}$$

Conclusion

In starbursts:

<u>Astroparticles</u>:
Strong CR production
- ❖ particles/field equipartition
- ❖ universal acceleration efficiency of SN

<u>Astrophysics</u>:
IMF top-heavy ($M_{low} \sim 2\ M_{\odot}$)
- ❖ higher T, σ_v → higher Jeans mass
- ❖ support from: colors + FIR lum, SNR counts

<u>Cosmology</u>:
Top-heavy IMF in all early SF galaxies?
- ❖ renormalize SFR(z)

Long live Elihu !