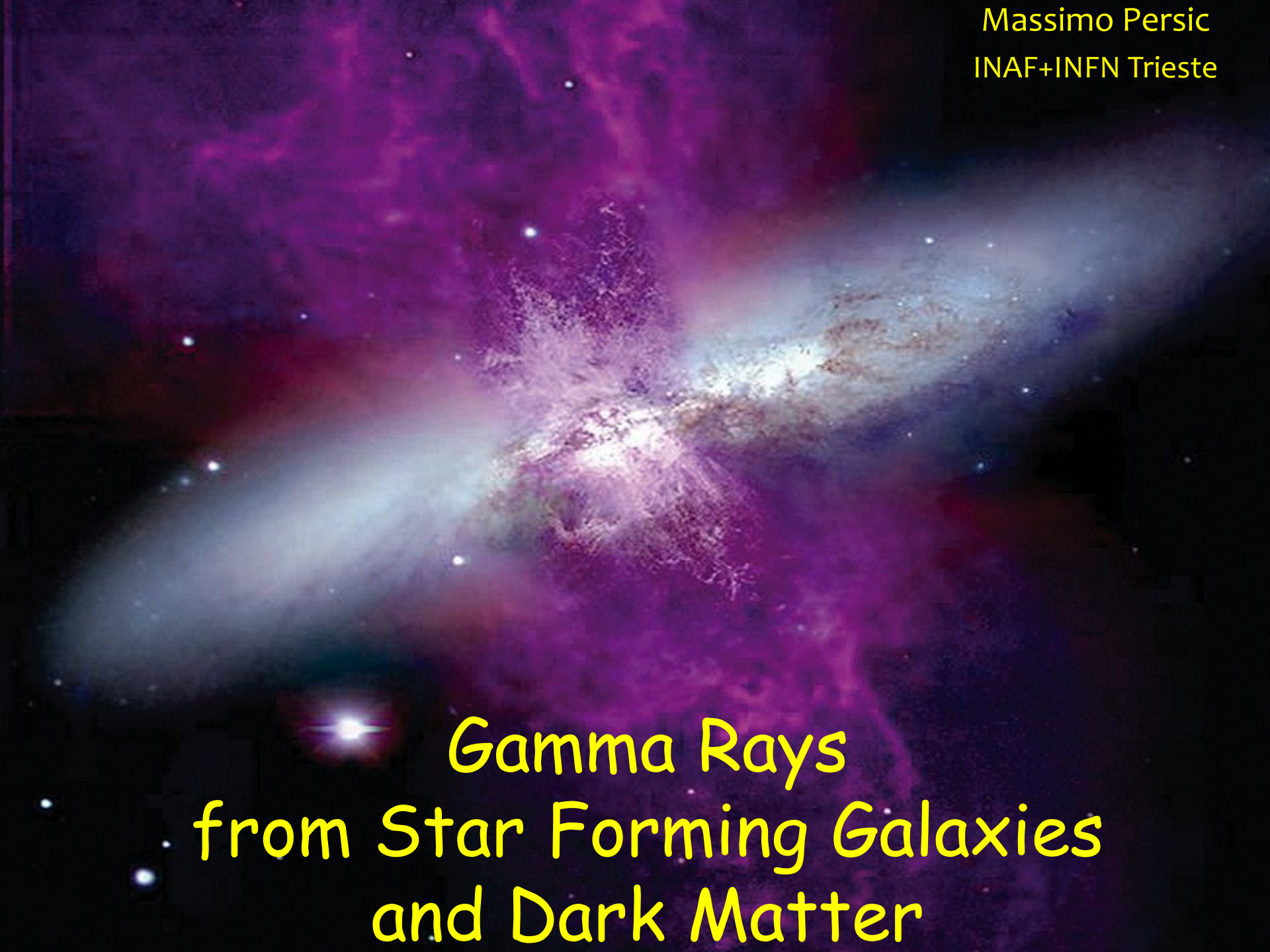
Massimo Persic
INAF+INFN Trieste



Gamma Rays from Star Forming Galaxies and Dark Matter

Non-Thermal plasma: $T_{ion} \neq T_{electron}$

f(***v***) of either species non-Maxwell Boltzmann

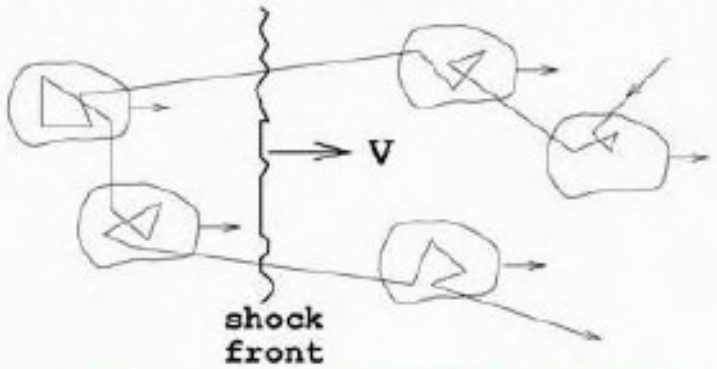
Particle Acceleration

Fermi Acceleration Mechanism

Stochastic energy gain in collisions with plasma clouds

1st order :

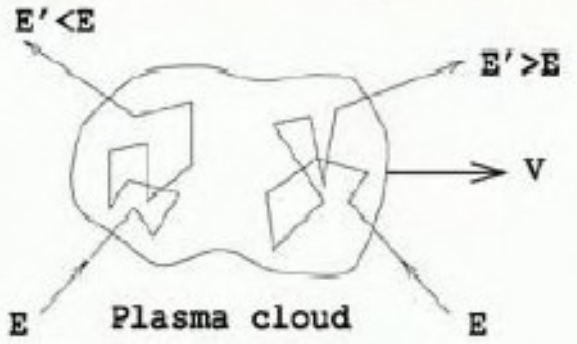
acceleration in strong shock wave (supernova ejecta, RG hot spots...



$$\frac{\Delta E}{E} \sim \beta \qquad \beta = \frac{V}{c} \lesssim 10^{-1}$$

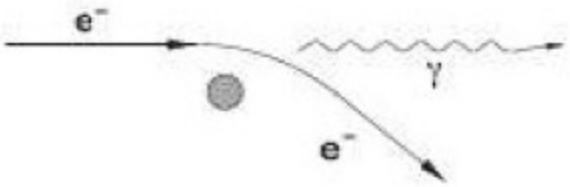
2nd order :

randomly distributed magnetic mirrors

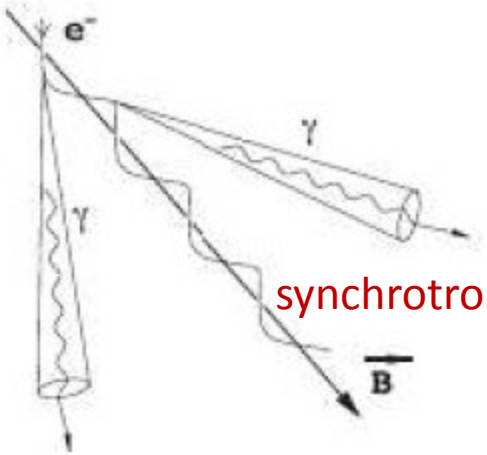


$$\frac{\Delta E}{E} \sim \beta^2 \qquad \beta = \frac{V}{c} \lesssim 10^{-4}$$

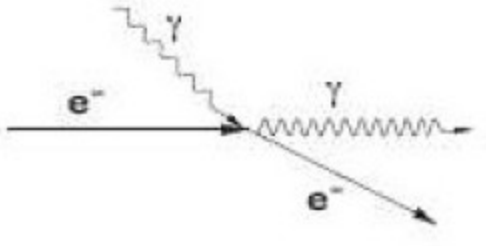
Radiation Processes



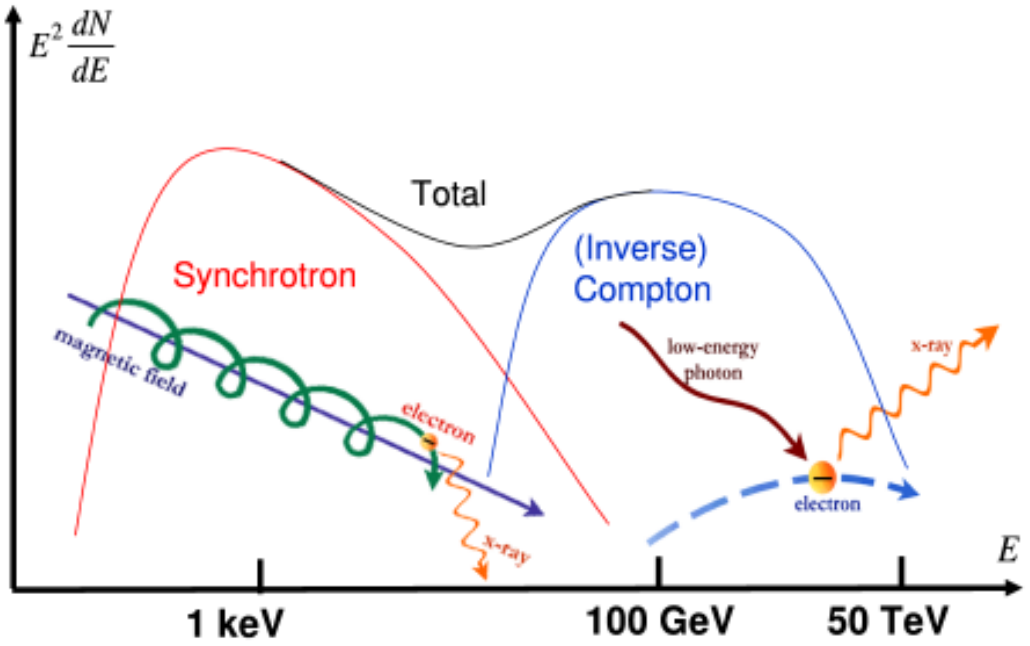
bremsstrahlung

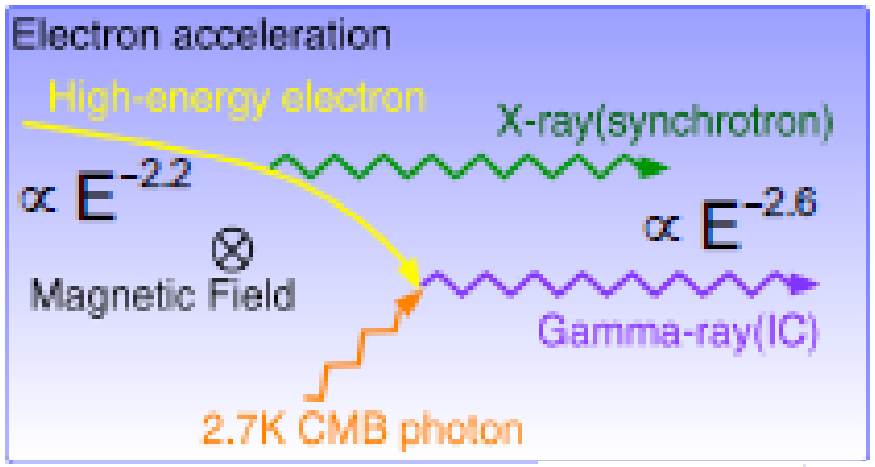


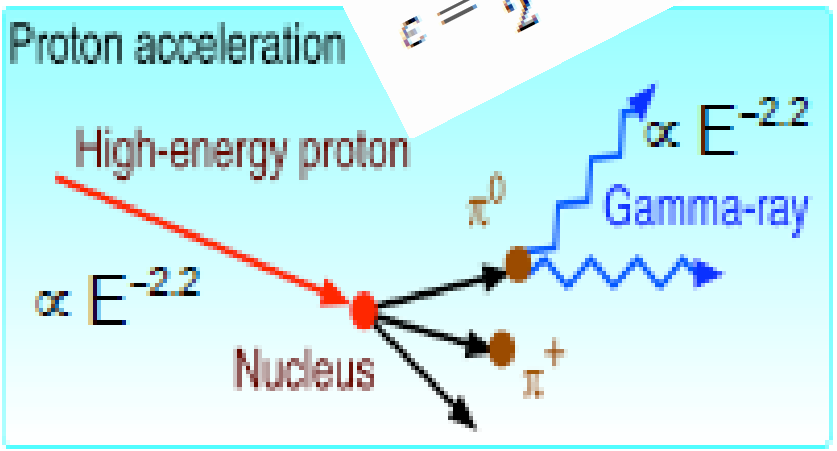
synchrotron



Inverse Compton

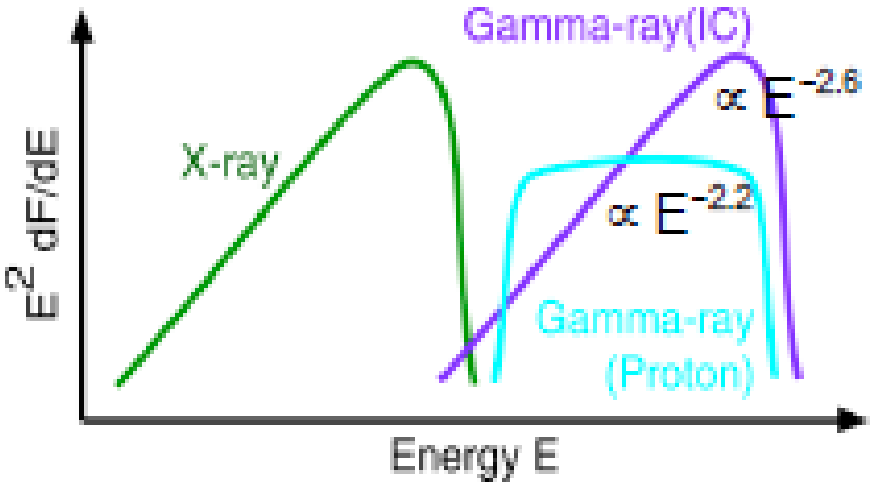






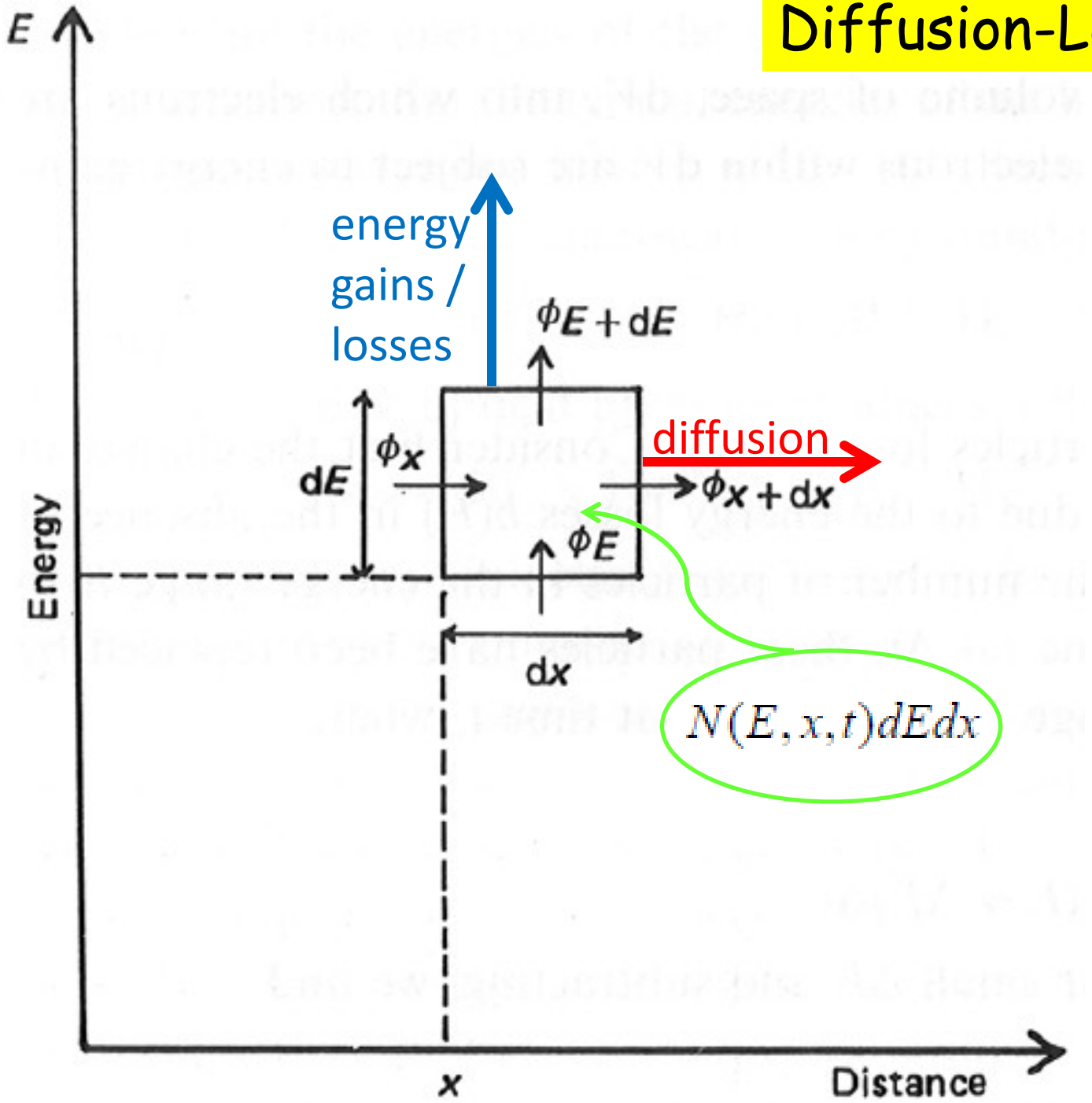
$$\varepsilon = \frac{1}{2} m_\pi c^2 \frac{1+\beta\cos\theta}{\sqrt{1-\beta^2}}$$

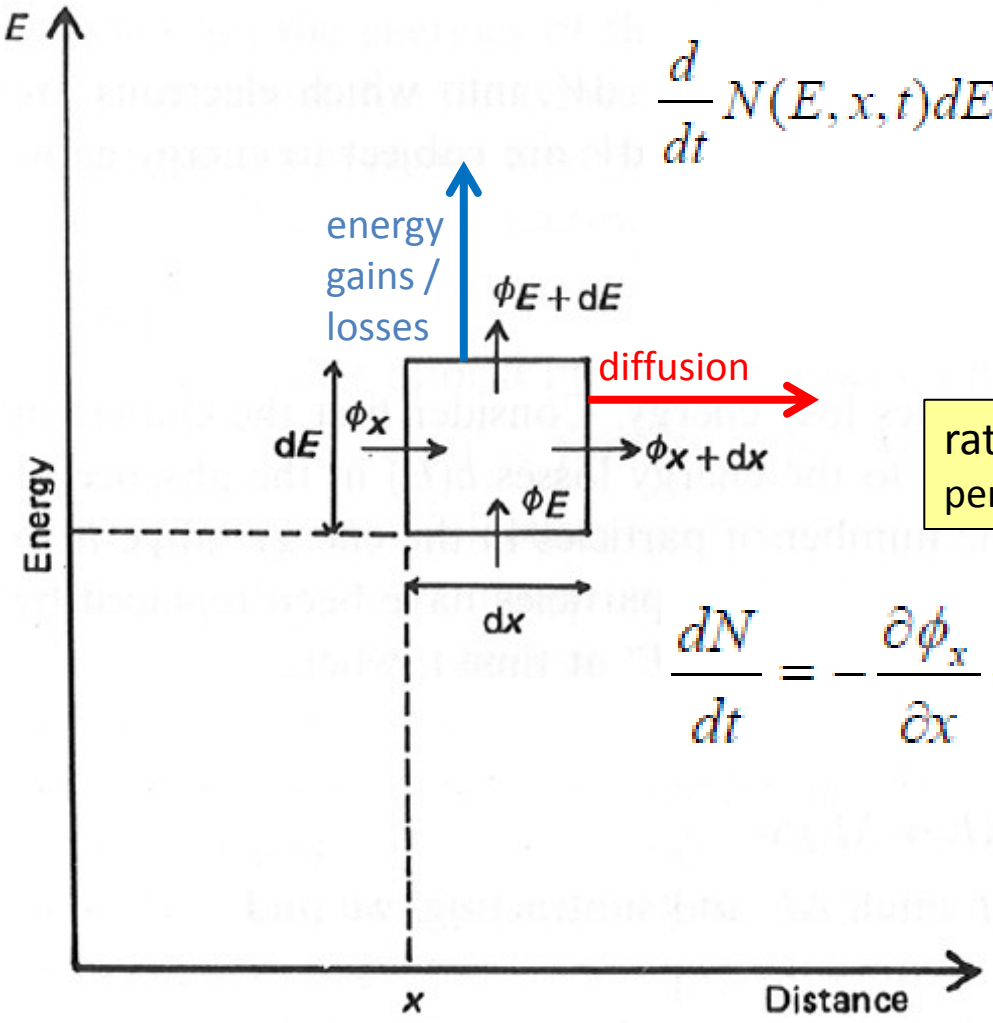
$$p + p \rightarrow \pi^+ + X \rightarrow \mu^+ + \nu_\mu + X \rightarrow e^+ + \nu_e + \bar{\nu_\mu} + \nu_\mu + X$$



- Background photons:
  - CMB, IR (UV heating), soft thermal X-rays
- Acceleration @ shocks:
  - In relativistic winds (pulsars, young stars)
  - Shell-type SNRs
  - Pulsar magnetosphere
- Variability:
  - Fast in compact sources

Diffusion-Loss Equation





$$\frac{d}{dt}N(E,x,t)dEdx = \left[\phi_x(E,x,t) - \phi_{x+dx}(E,x+dx,t)\right]dE + \left[\phi_E(E,x,t) - \phi_{E+dE}(E+dE,x,t)\right]dx + Q(E,x,t)dEdx,$$

rate of particles production per unit volume of coord space

$$\frac{dN}{dt} = -\frac{\partial \phi_x}{\partial x} - \frac{\partial \phi_E}{\partial E} + Q$$

by definition: $\phi_x = -D\frac{\partial N}{\partial x}$

$$\Rightarrow \quad \frac{dN}{dt} = D\frac{\partial^2 N}{\partial x^2} - \frac{\partial \phi_E}{\partial E} + Q$$

energy loss for particles of energy E

$$-dE/dt = b(E) \quad \Rightarrow \quad N(E)\frac{dE}{dt} = \phi_E = -b(E)N(E)$$

$$\boxed{\frac{dN(E)}{dt} = \frac{d}{dE}\left[b(E)N(E)\right] + Q(E,t) + D\nabla^2 N(E)}$$

Energy loss processes: protons

- Ionization losses

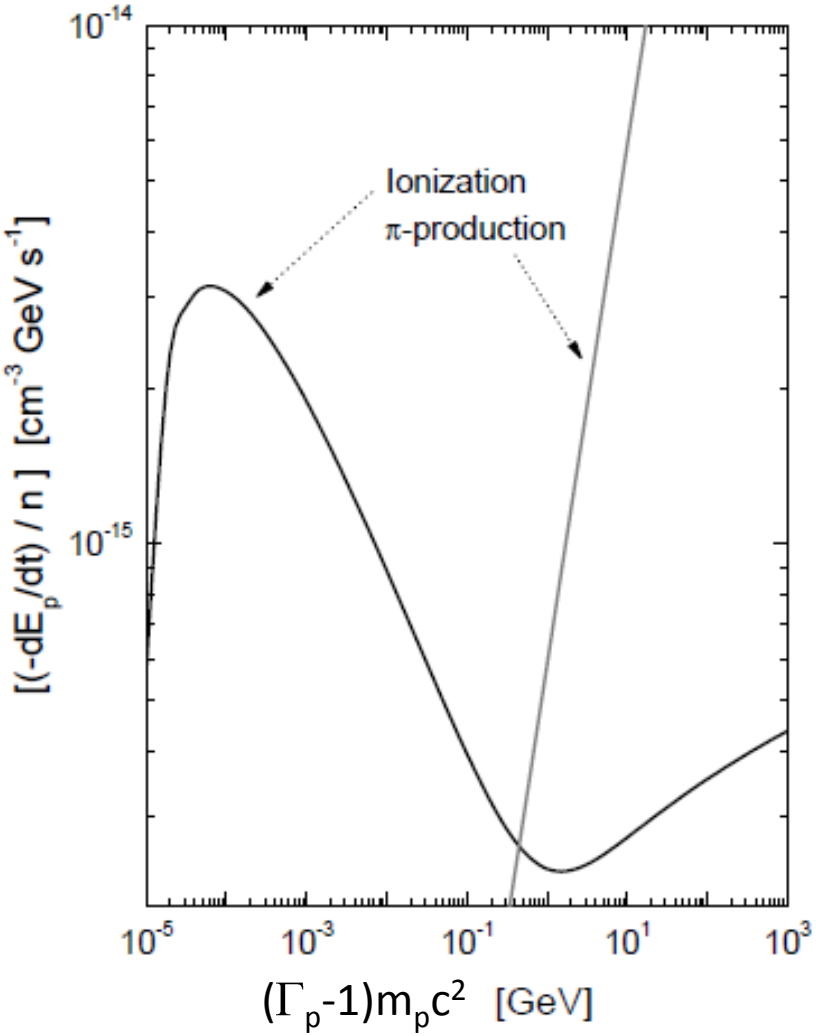
$$-\left(\frac{d\Gamma_p}{dt}\right)_{\mathrm{Ion},p} \cong \begin{cases} \cdot^{14}\, n_p\ (1-\Gamma_p^{-2})^{-1/2}\,[10.9 + 2\ln\Gamma_p + \ln(1-\Gamma_p^{-2}) + (1-\Gamma_p^{-2})] & s^{-1} \\ \therefore\ 10^{-15}\, n_p\,[26.73 + 3\ln(\Gamma_p)] & s^{-1} \end{cases}$$

$\Gamma_p > 2000$

- Pion production

$$-\left(\frac{d\Gamma_p}{dt}\right)_{\mathrm{Pion},p} \cong 3.7 \times 10^{-13}\, n_p\ (\Gamma_p - 1)$$

$\Gamma_p > 2.38$ ($\rightarrow$ 1.22 GeV)



Energy loss processes: electrons

$$b(\gamma) = b_{\rm Coul}(\gamma) + b_{\rm syn}(\gamma) + b_{\rm IC}(\gamma) + b_{\rm brem}(\gamma) + b_{\rm AW}(\gamma)$$

- Coulomb interactions with thermal electrons

$$b_{\rm Coul}(\gamma) \approx 1.2 \times 10^{-12} n_e \left[1.0 + \frac{\ln(\gamma/n_e)}{75} \right] \ {\rm s}^{-1}$$

- synchrotron radiation

$$b_{\rm syn}(\gamma) = \frac{4}{3} \frac{\sigma_{\rm T}}{m_e c} \gamma^2 U_B = 1.30 \times 10^{-21} \gamma^2 \left(\frac{B}{1\ \mu{\rm G}} \right)^2 \ {\rm s}^{-1}$$

- Inverse Compton (IC) scattering

$$b_{\rm IC}(\gamma) = \frac{4}{3} \frac{\sigma_{\rm T}}{m_e c} \gamma^2 U_r = 1.37 \times 10^{-20} \gamma^2 (1+z)^4 \ {\rm s}^{-1}$$

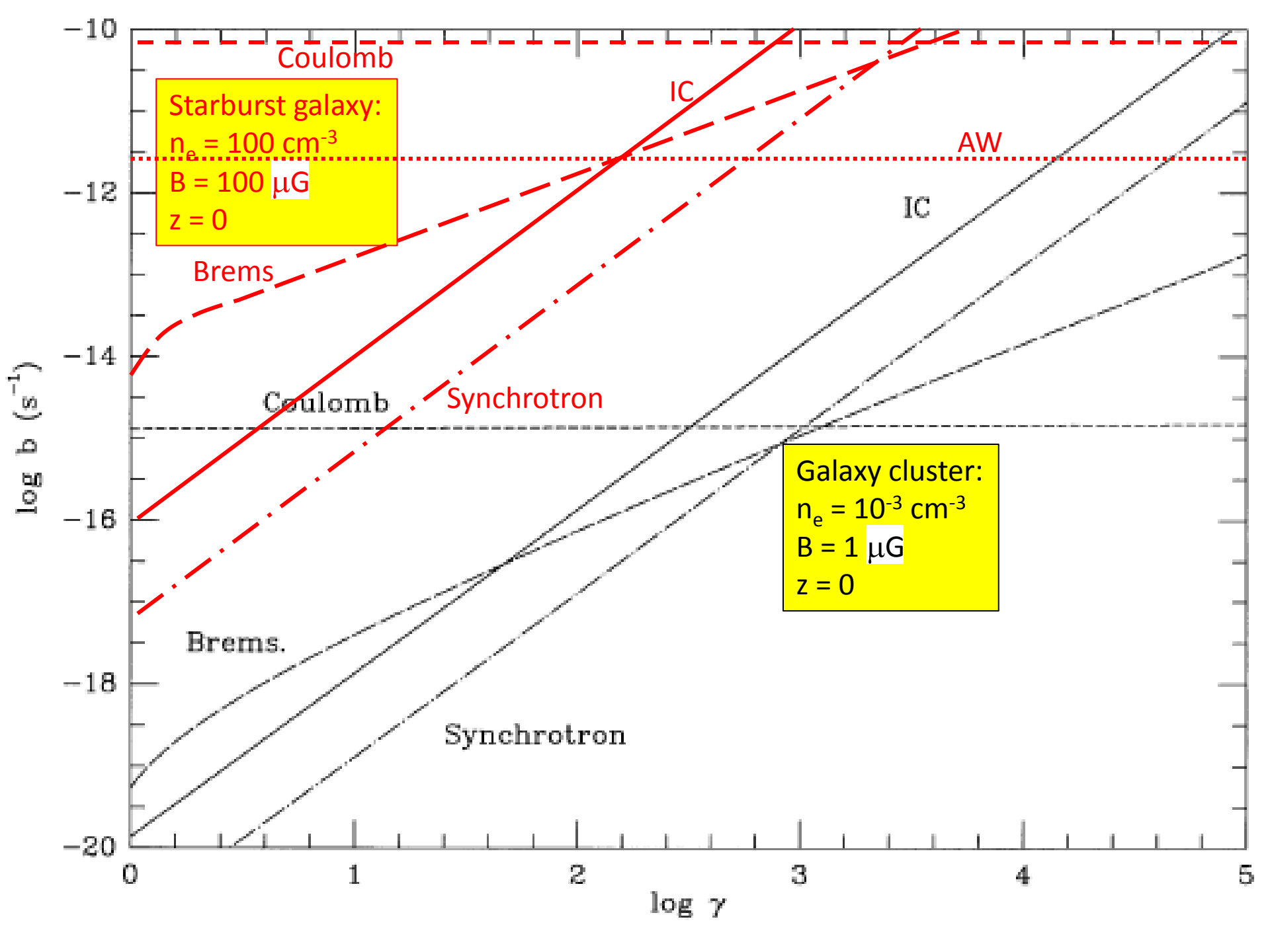
… for $U_r = 4\ 10^{-13}$ erg cm^{-3}

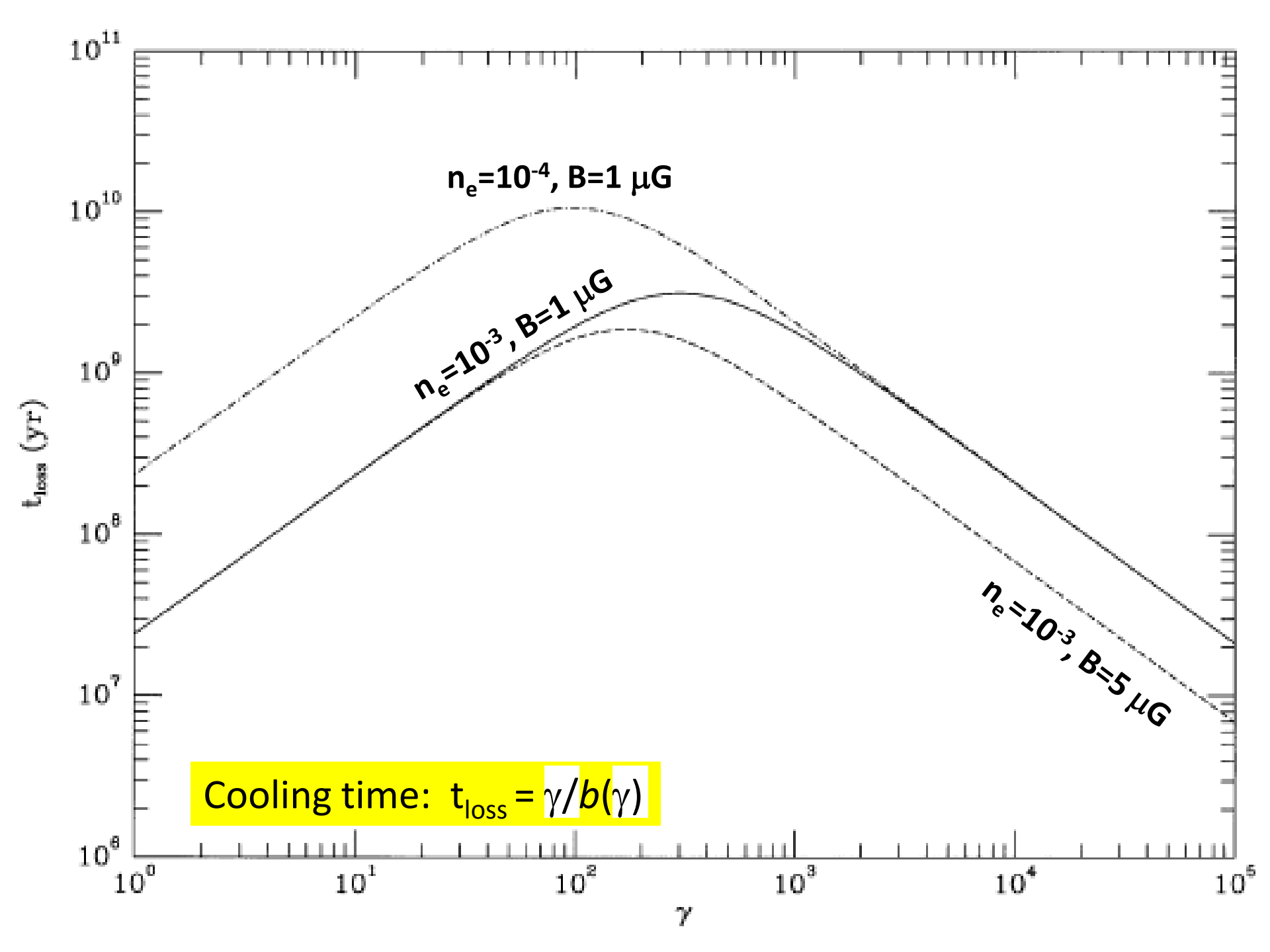
- bremsstahlung radiation

$$b_{\rm brem}(\gamma) \approx 1.51 \times 10^{-16} n_e \gamma [\ln(\gamma) + 0.36] \ {\rm s}^{-1}$$

- Scattering by Alfvèn waves

$b_{\rm AW} = -B\,(4\pi\rho)^{-1/2}/L\ \gamma = 3 \times 10^{-16}\ (B/\mu{\rm G})\ n_e\ (L/0.3\ {\rm kpc})^{-1}\ \gamma\ {\rm s}^{-1}$


Coulomb
IC
AW
Starburst galaxy:
n_e = 100 cm^{-3}
B = 100 μG
z = 0
Brems
IC
Coulomb
Synchrotron
Galaxy cluster:
n_e = 10^{-3} cm^{-3}
B = 1 μG
z = 0
Brems.
Synchrotron
log b (s^{-1})
log γ
−10
−12
−14
−16
−18
−20
0
1
2
3
4
5


$n_e=10^{-4}$, B=1 μG
$n_e=10^{-3}$, B=1 μG
$n_e=10^{-3}$, B=5 μG
Cooling time: $t_{loss} = \gamma/b(\gamma)$
t_{loss} (yr)
γ
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}

HE Gamma Rays in Galaxies

MP, Rephaeli & Arieli 2008, A&A, 486, 143
Rephaeli, Arieli & MP 2010, MNRAS, 401, 473
MP & Rephaeli 2010, MNRAS, 403, 1569

- electron spectrum

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

- synchr. emissivity

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

- electron spectrum: normalization, energy density

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

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

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

- particle/field energy density equipartition

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

- p/e energy density ratio

$$\kappa \equiv \frac{U_{\rm p}}{U_{\rm e}} = \frac{\int_{T_0}^{\infty} N_{\rm p}(T)\, T\, {\rm d}T}{\int_{T_0}^{\infty} N_{\rm e}(T)\, T\, {\rm d}T} = \frac{\left[\frac{T_0^2}{c^2}+2T_0 m_{\rm p}\right]^{\frac{q-1}{2}} \int_{T_0}^{\infty} T(T+m_{\rm p}c^2)\left[\frac{T^2}{c^2}+2Tm_{\rm p}\right]^{-\frac{q+1}{2}} {\rm d}T}{\left[\frac{T_0^2}{c^2}+2T_0 m_{\rm e}\right]^{\frac{q-1}{2}} \int_{T_0}^{\infty} T(T+m_{\rm e}c^2)\left[\frac{T^2}{c^2}+2Tm_{\rm e}\right]^{-\frac{q+1}{2}} {\rm d}T}$$

T_0 = few keV

- p/e ratio

$$\frac{N_{\rm p}(T)}{N_{\rm e}(T)} \simeq \left(\frac{m_{\rm p}}{m_{\rm e}}\right)^{\frac{q-1}{2}} \left(\frac{T+m_{\rm p}c^2}{T+m_{\rm e}c^2}\right) \left(\frac{T+2m_{\rm p}c^2}{T+2m_{\rm e}c^2}\right)^{-\frac{q+1}{2}} \simeq \begin{cases} 1 & T << m_{\rm e}c^2\,; \\ [T/(m_{\rm e}c^2)]^{\frac{q-1}{2}} & m_{\rm e}c^2 << T << m_{\rm p}c^2 \\ (\frac{m_{\rm p}}{m_{\rm e}})^{\frac{q-1}{2}} & m_{\rm p}c^2 << T\,. \end{cases}$$

⇨ q=2.3 → $\kappa = U_p/U_e \approx 15$ $\quad N_p/N_e\,|_{>>1\,\rm GeV} \approx 1.3\times10^2$

- equipartition magnetic field

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

- CRp energy density

$$U_p = \frac{B^2}{8\pi\,(1+\kappa^{-1})}$$

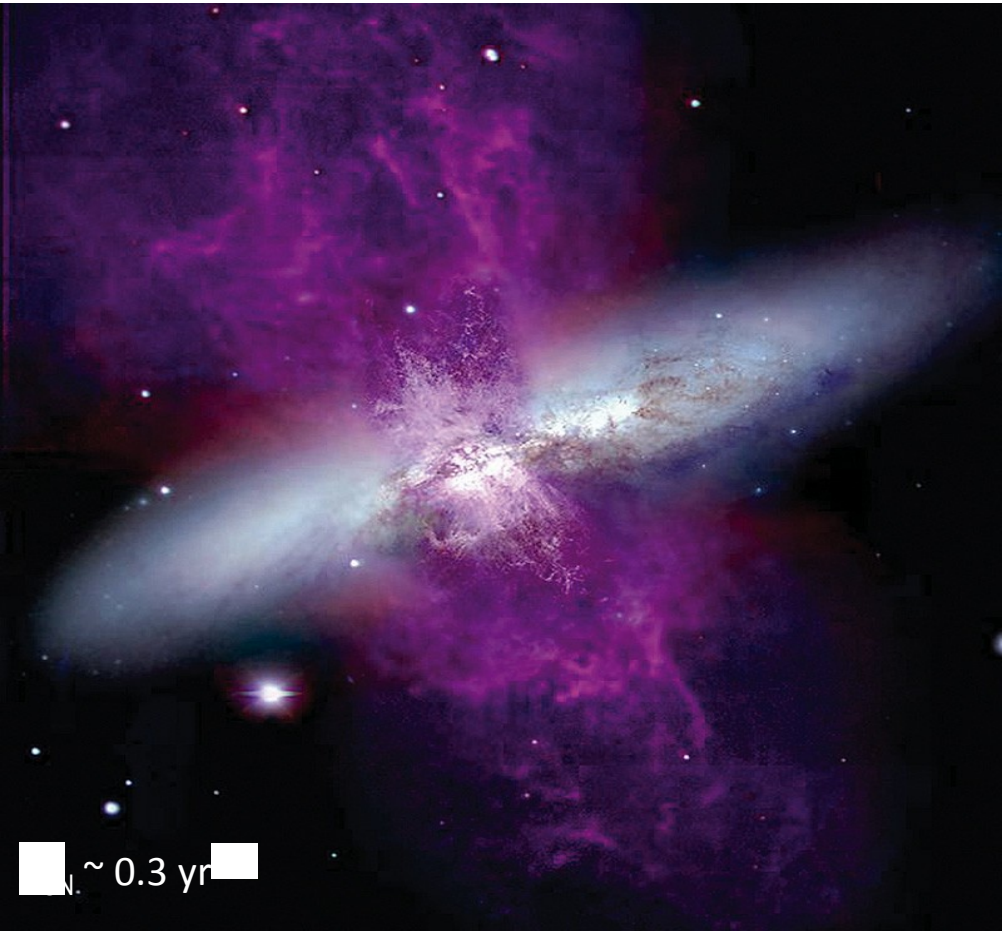
$$B_{\rm eq} = \left\{\frac{7.44\times10^{-21}}{1+\chi}\left[1+\frac{\kappa(q)}{1+\chi}\right]\frac{\gamma_1^{2-q}\,250^{q/2}\,\psi}{(q-2)\,a(q)}\right\}^{\frac{2}{5+q}}$$

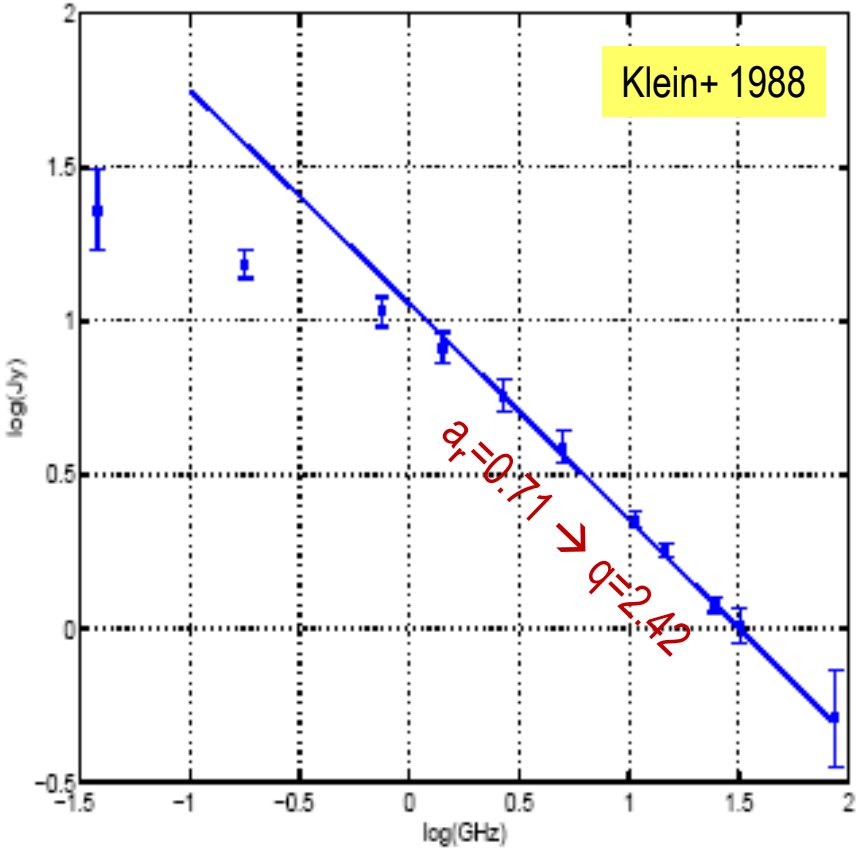
$$U_{\rm p}\left[1+\frac{1+\chi}{\kappa(q)}\right] = \frac{B^2}{8\pi}$$

primary/secondari electron ratio ~ 0.5

M82 d=3.6 Mpc
r(SB)= 0.3 kpc
f_{1GHz} = 10 Jy

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





α_r=0.71 → q=2.42

$L_{8-1000\mu m} = 2.2\times10^{44}$ erg s $^{-1}$ → SFR ~10 $M_{\odot}yr^{-1}$

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

(… M82 cont'd)

VHE γ-ray emission

analytical approx.

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

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

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

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

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

External disk: r>0.3 kpc

Gas: flat, thin, exponential disk: $M_g = 2.5\times10^9 M_\otimes$

$\Sigma(R) = \Sigma(0)\ e^{-R/R_d}$

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

$R_d = 0.82$ kpc

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

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

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

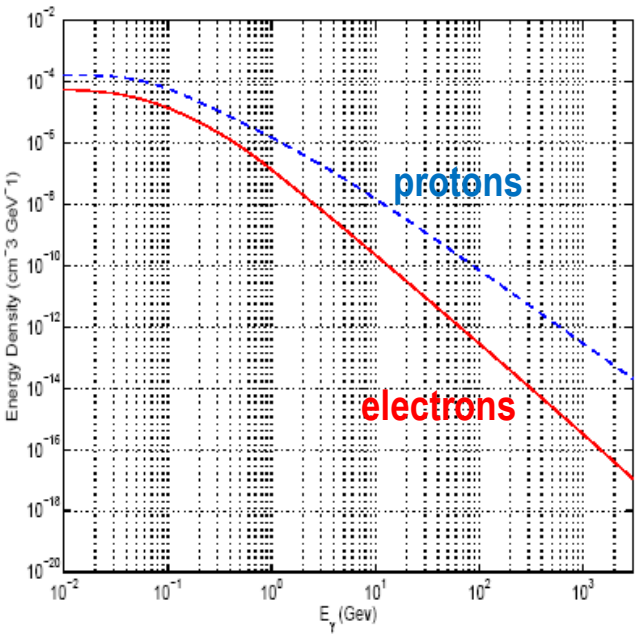
(… M82 cont'd)

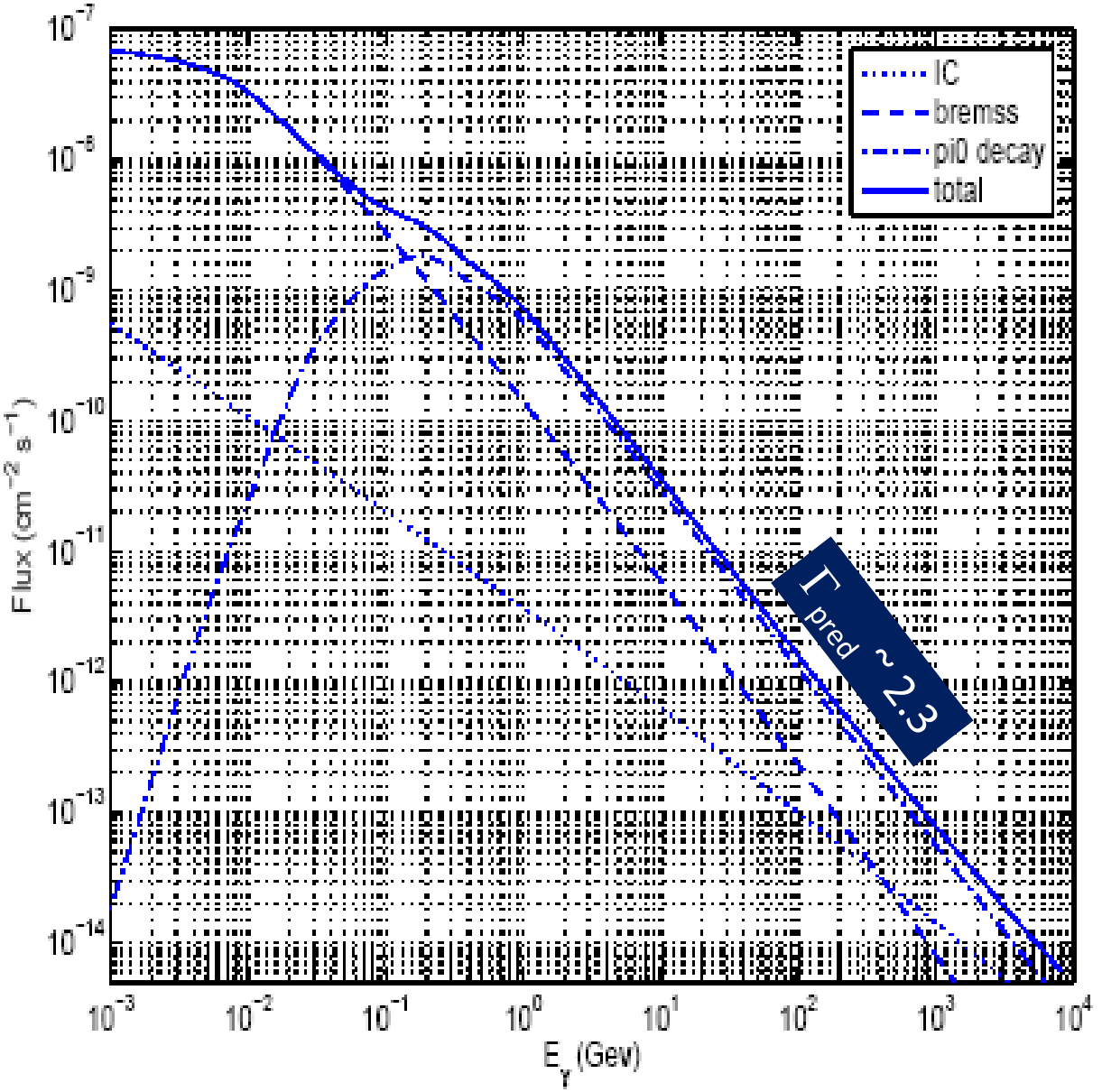
numerical treatment
loss-propagation model

… same structure parameters

CR/field energy equip.
p/e theoretically assumed

injection part. spectrum: q=2
… interactively →
$N_e \sim 10^{-4}$ cm^{-3}
N_p/N_e (>>1 GeV) ~ 50,
$B_0 \sim 180$ μG





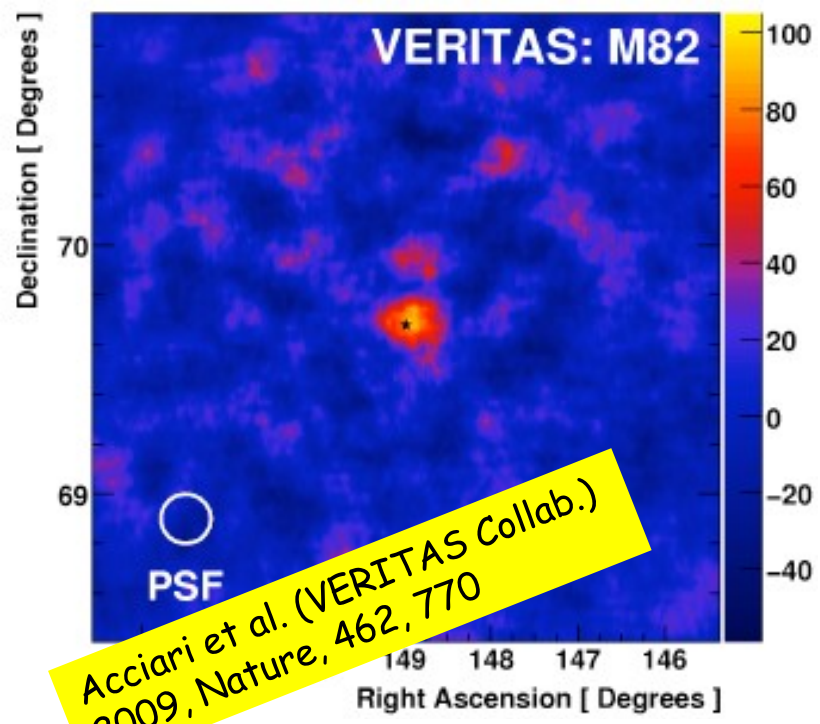
$F_{>100MeV}$ = E-8 cm^{-2} s^{-1}

$F_{>100GeV}$ = 2.5E-12 cm^{-2} s^{-1}

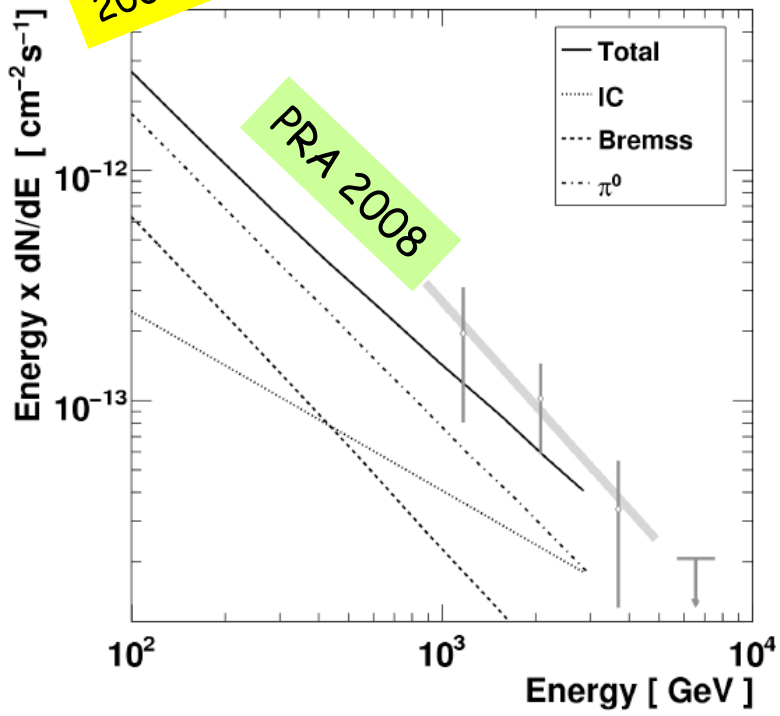
≥1/2 sens. of MAGIC-II, VERITAS

(… M82 cont'd)

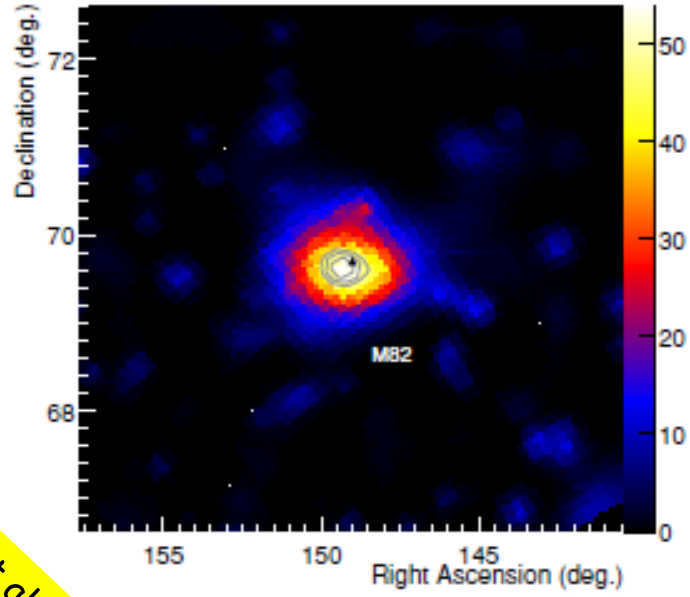
M82 detection



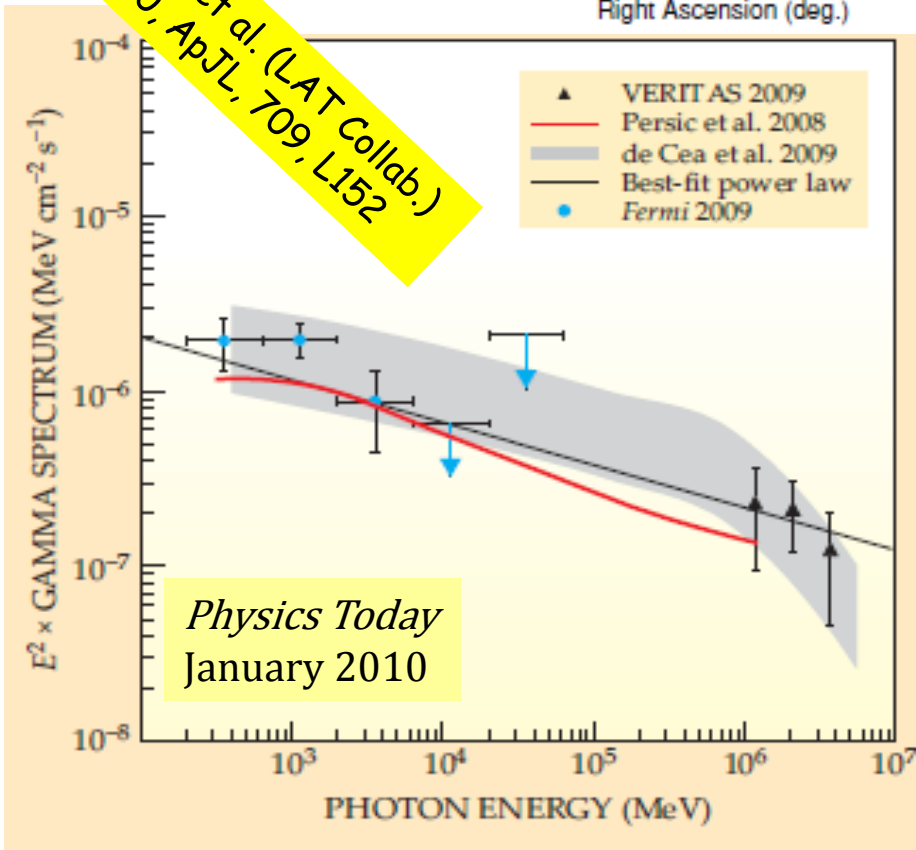
Acciari et al. (VERITAS Collab.) 2009, Nature, 462, 770



PRA 2008



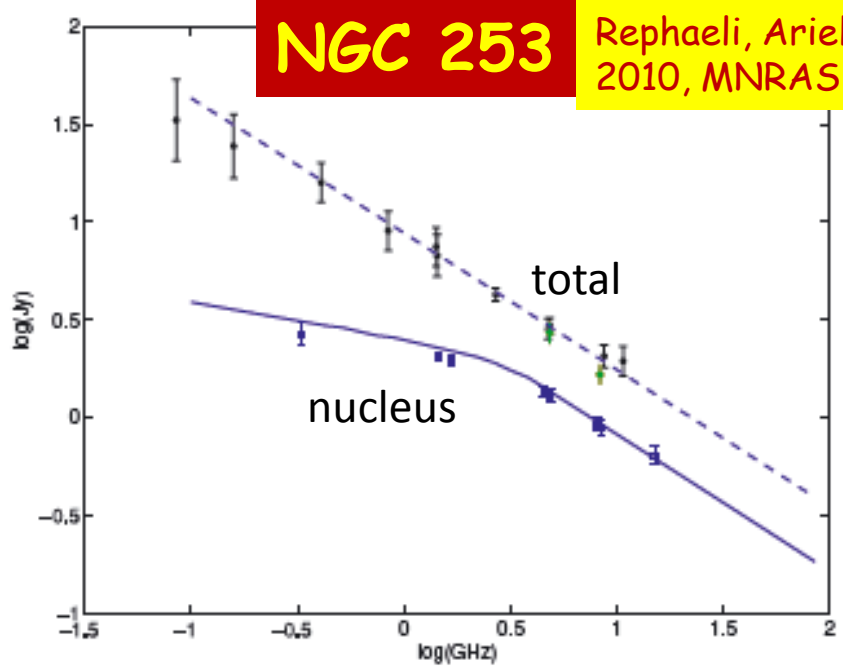
Abdo et al. (LAT Collab.) 2010, ApJL, 709, L152

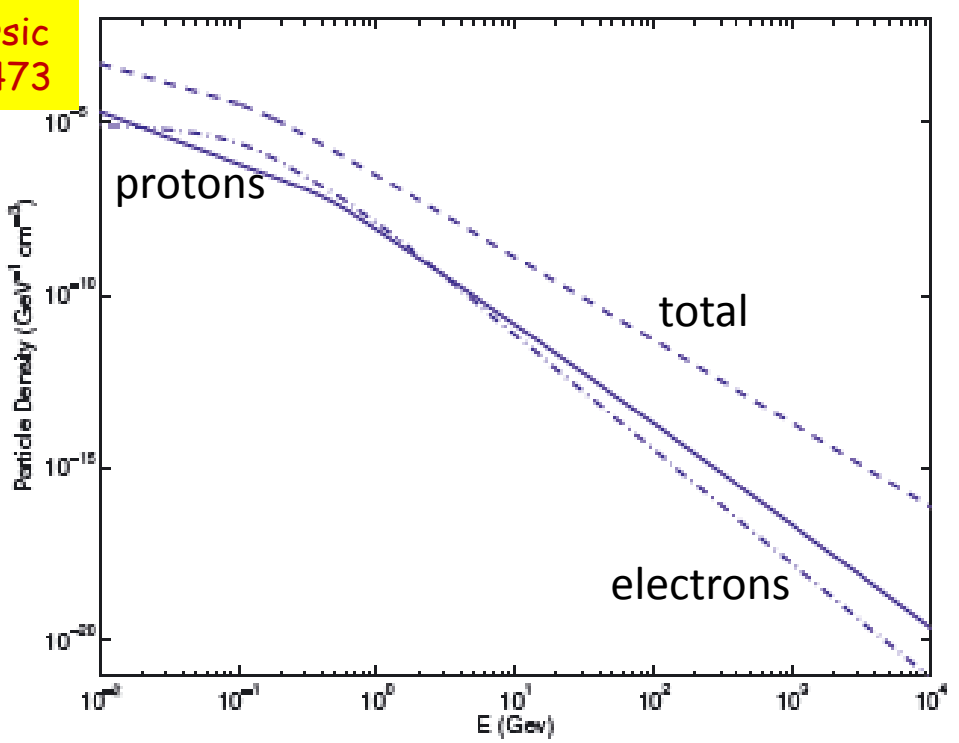


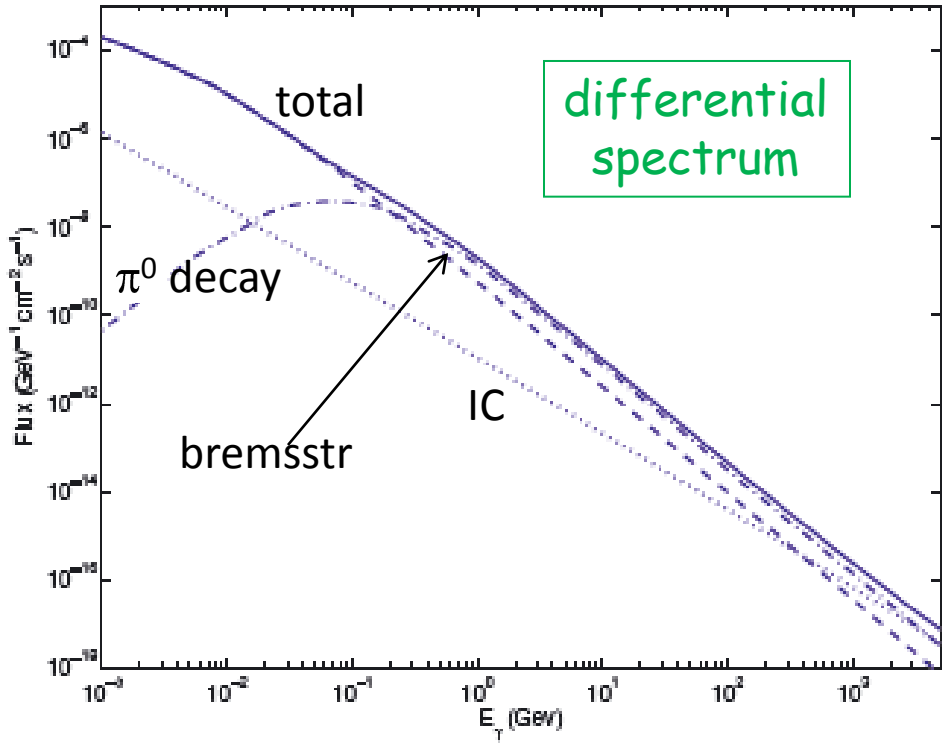
Physics Today January 2010

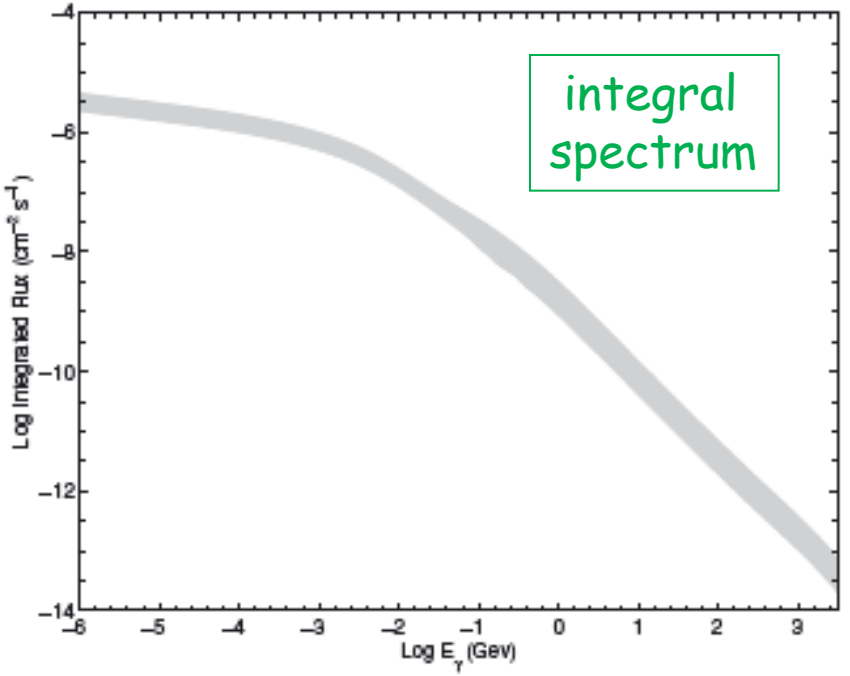
NGC 253

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





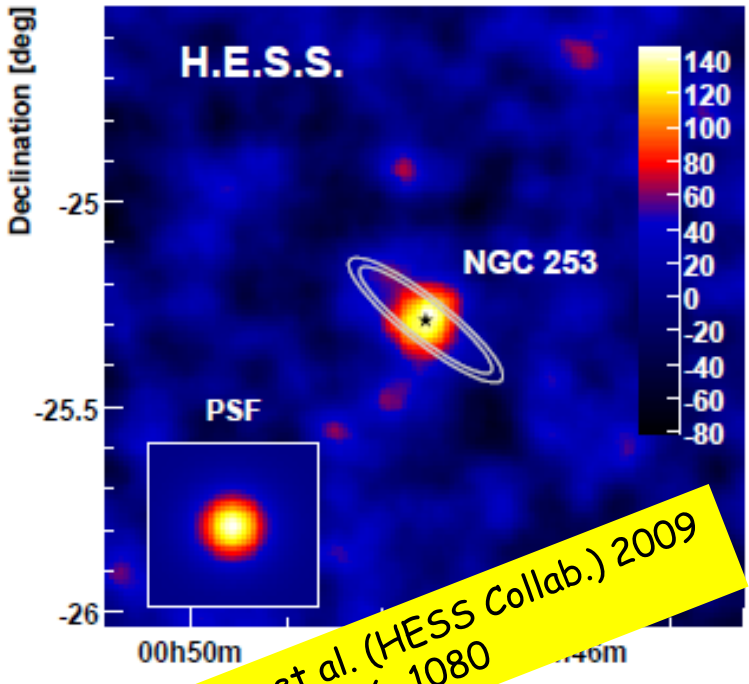




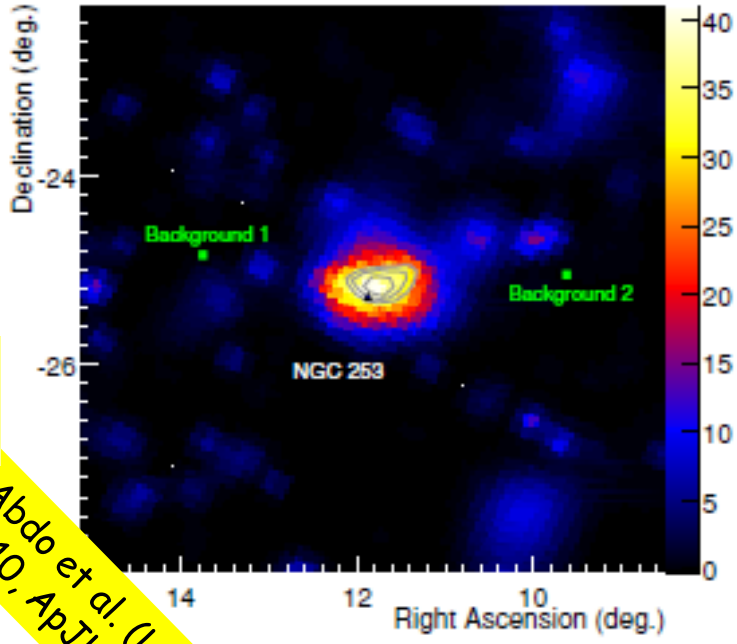
(… NGC253 cont'd)

NGC 253 detection

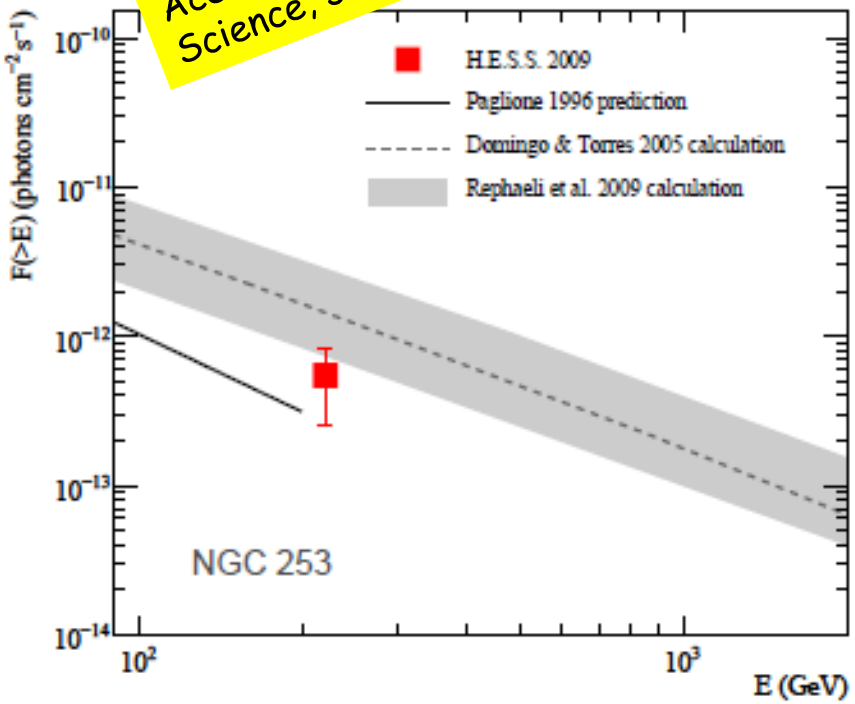
U_p ~ 150 eV cm^{-3}
in SB nucleus

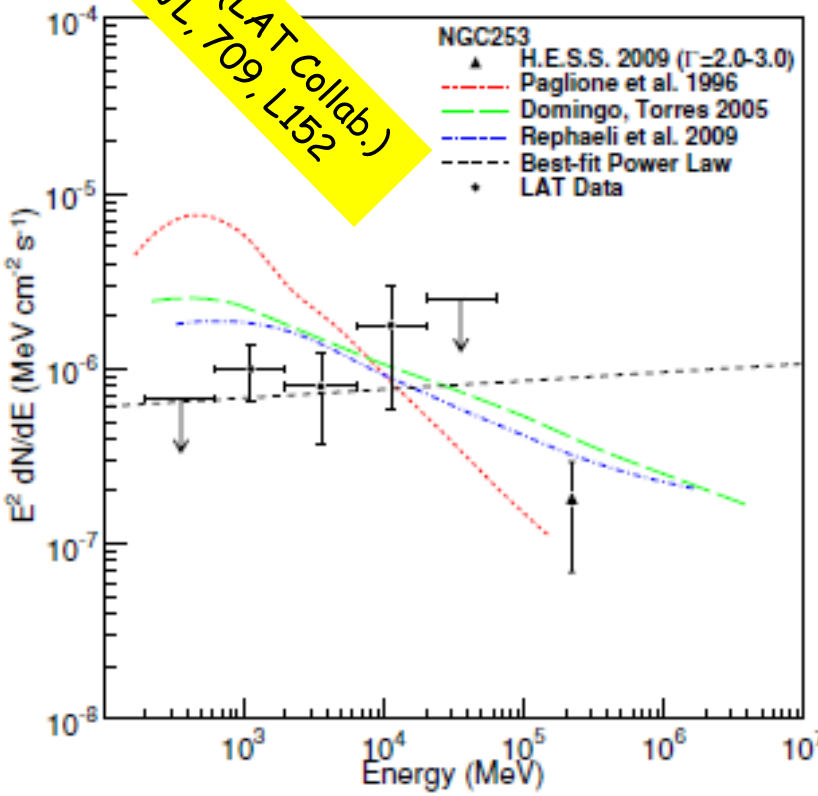


Acero et al. (HESS Collab.) 2009 Science, 326, 1080



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



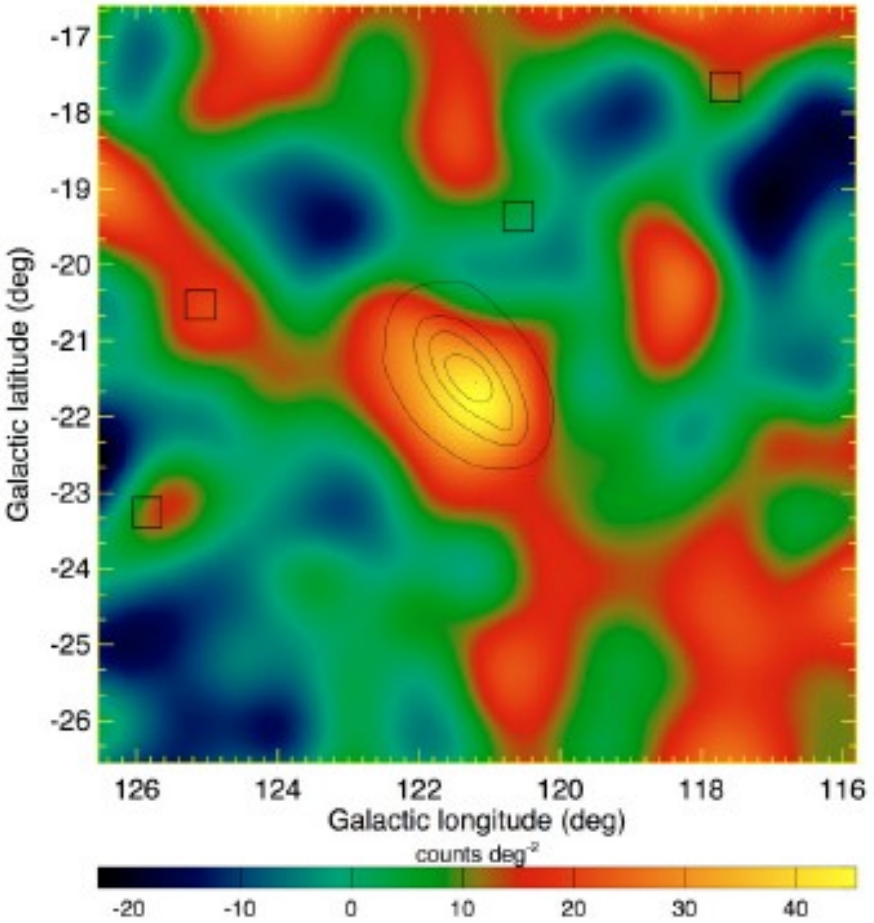


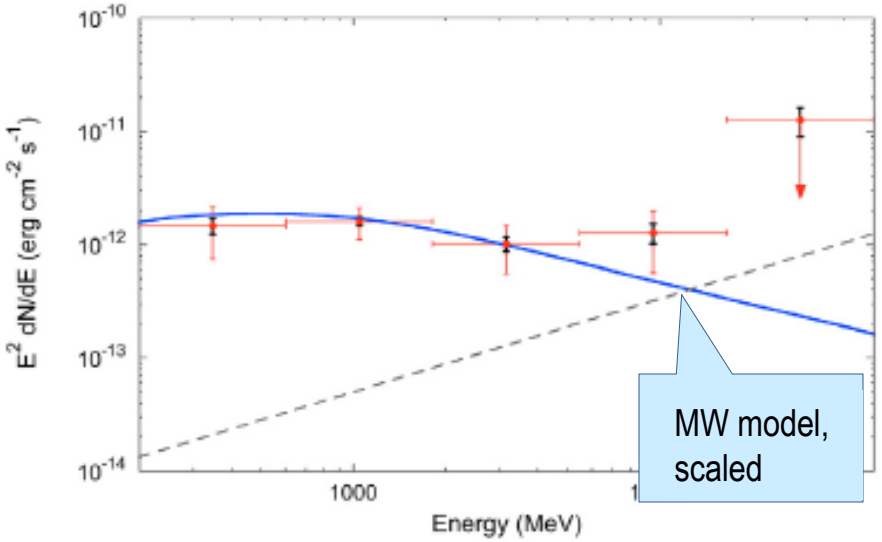
2. U_p from γ-rays

M31 (Andromeda Galaxy)

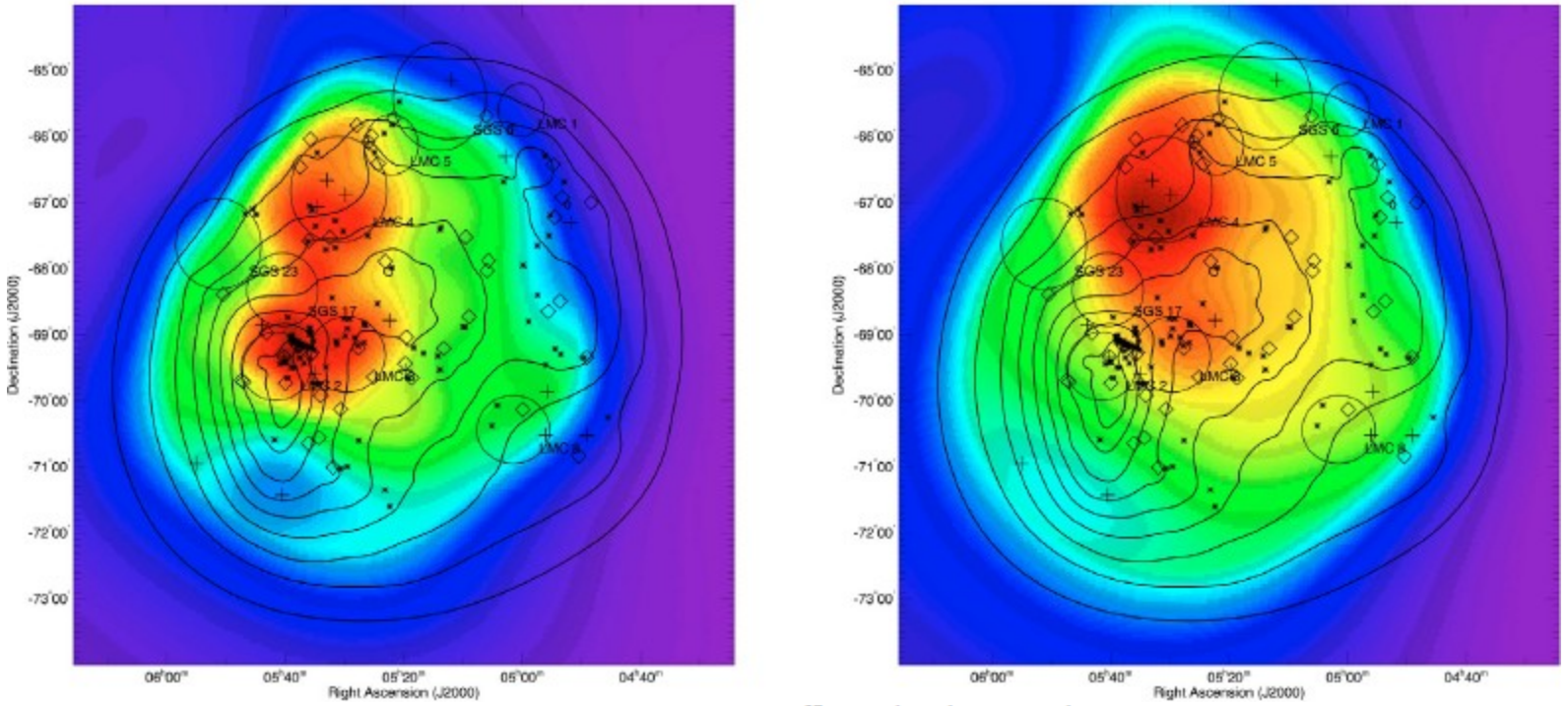
Abdo et al. (LAT Collab.) 2010, A&A, 523, L2

Galaxy	d kpc	M_{HI} $10^8\ M_\odot$	M_{H_2} $10^8\ M_\odot$	SFR $M_\odot\ yr^{-1}$	F_γ 10^{-8} ph cm^{-2} s^{-1}	L_γ 10^{41} ph s^{-1}
MW	...	$35 \pm 4^{(7)}$	$14 \pm 2^{(7)}$	$1-3^{(19)}$	...	$11.8 \pm 3.4^{(28)}$
M 31	$780 \pm 33^{(1)}$	$73 \pm 22^{(8)}$	$3.6 \pm 1.8^{(14)}$	$0.35-1^{(19)}$	0.9 ± 0.2	6.6 ± 1.4

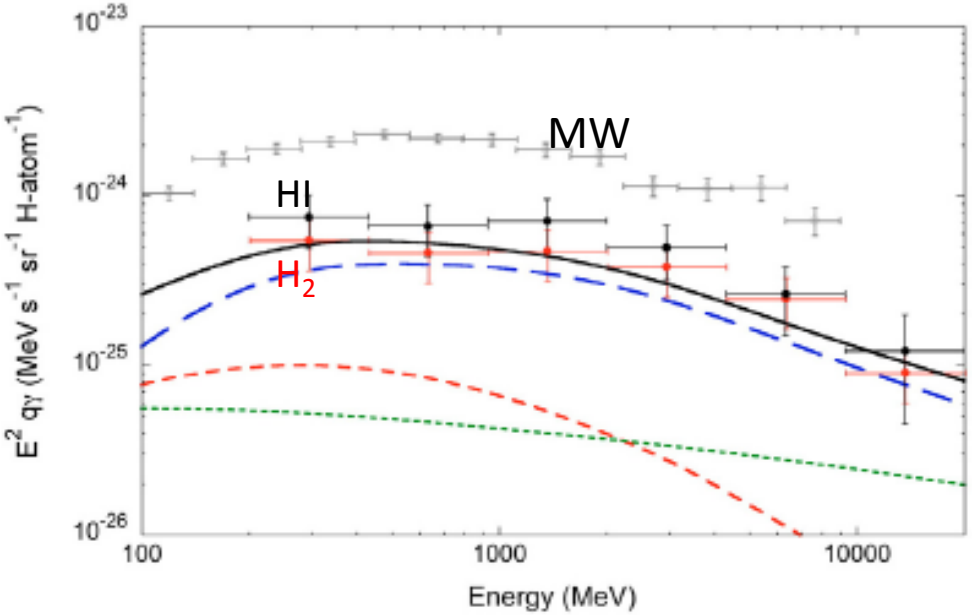




$U_p \sim 0.36$ eV cm^{-3}



Integrated >100 MeV emissivity maps of the LMC in units of 10^{-27} ph s^{-1} sr^{-1} H-atom^{-1} for $\mathcal{H}_1$ (*left panel*) and $\mathcal{H}_2$ (*right panel*).



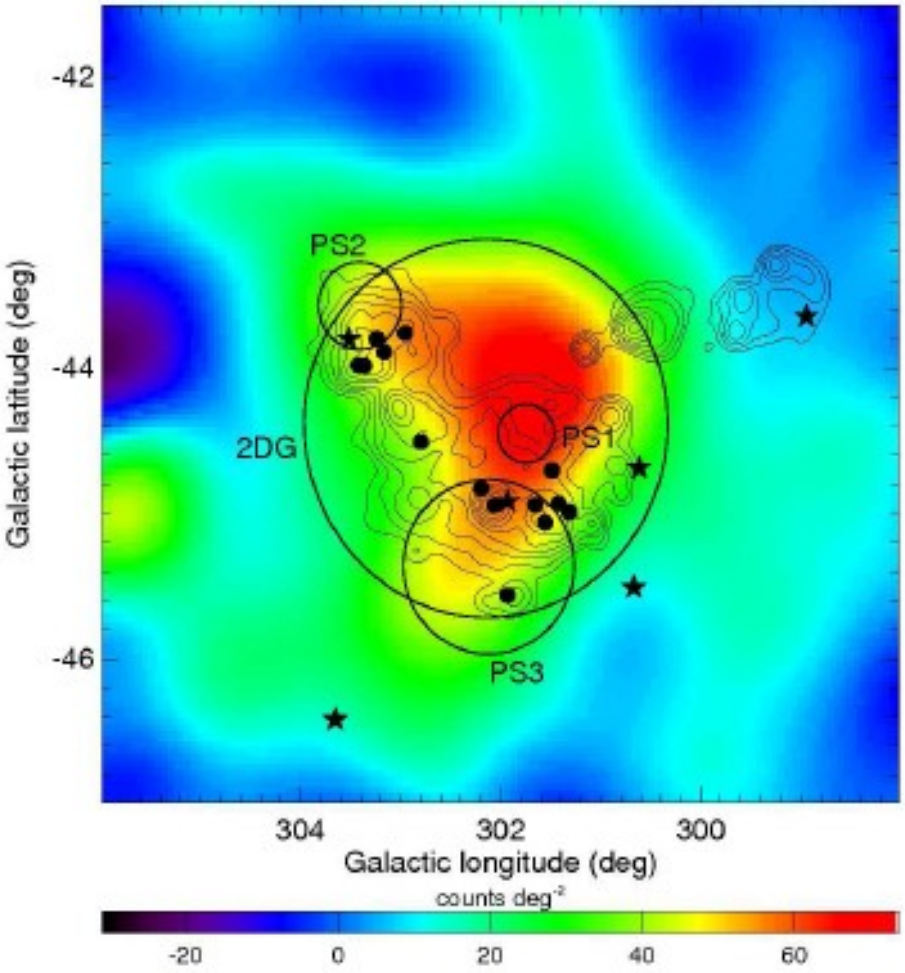
Large Magellanic Cloud (LMC)

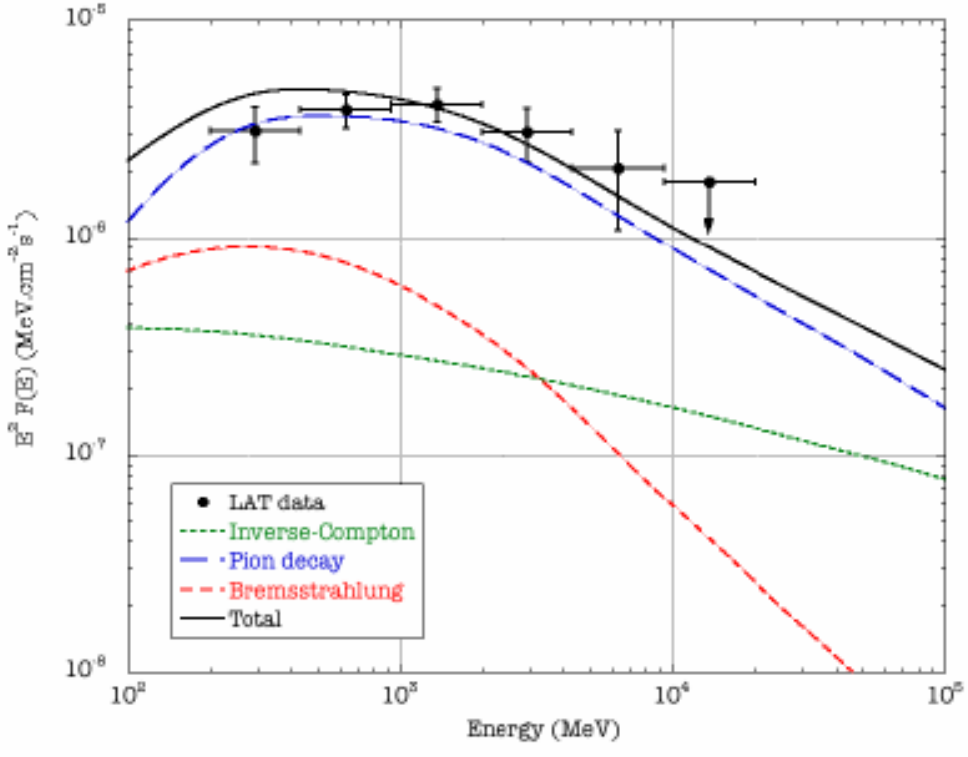
Abdo et al. (LAT Collab.)
2010, A&A, 512, 7

U_p ~ 0.2-0.3 eV cm^{-3}

Small Magellanic Cloud (SMC)

Abdo et al. (LAT Collab.)
2010, A&A, 523, A46





$U_p \sim 0.15$ eV cm^{-3}

Adapted from:

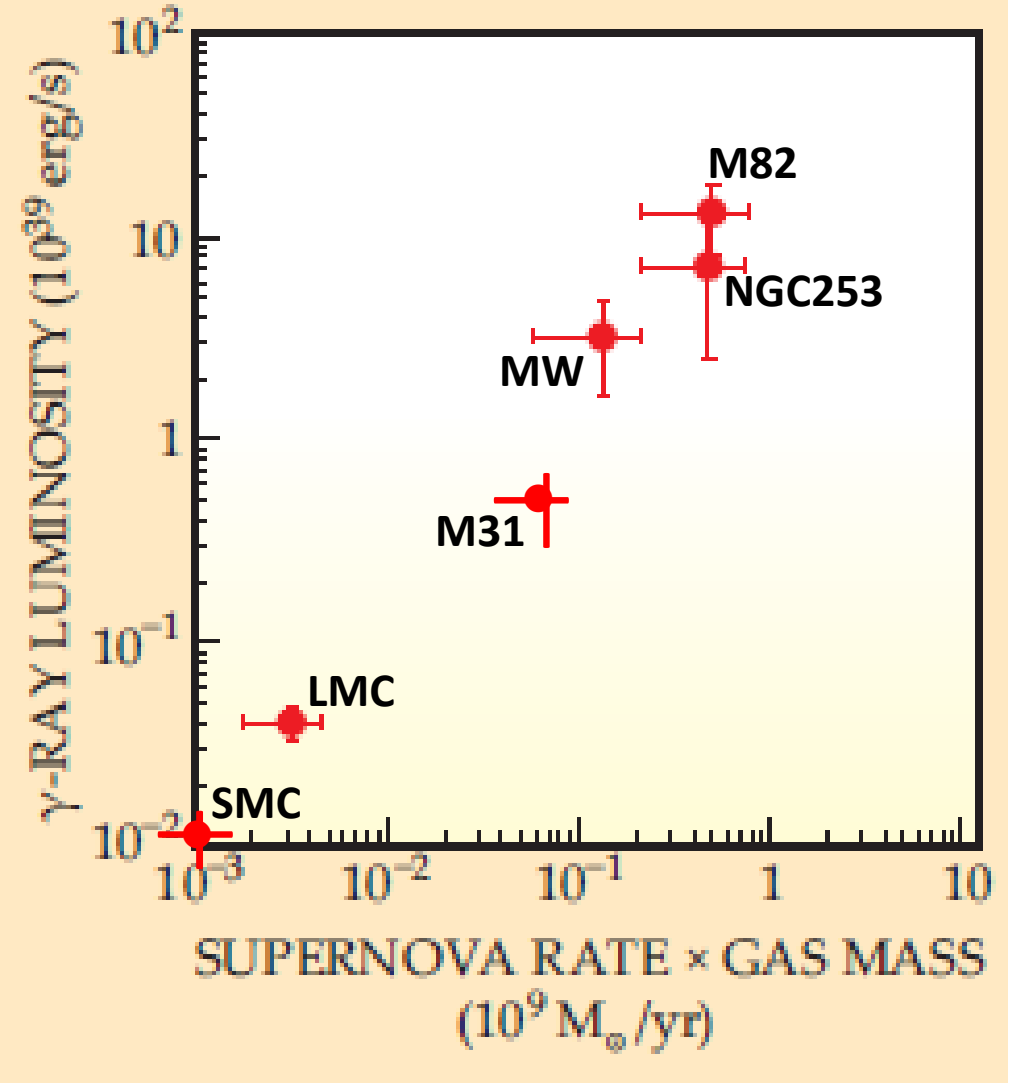
- Abdo et al. (LAT Collab.) 2010, ApJL, 709, L152;
- *Physics Today* (Jan. 2010)

$$L_\gamma(\geq \epsilon) = \int_V g_\gamma(\geq \epsilon)\, n\, U_P\, dV \quad \mathrm{s}^{-1}$$

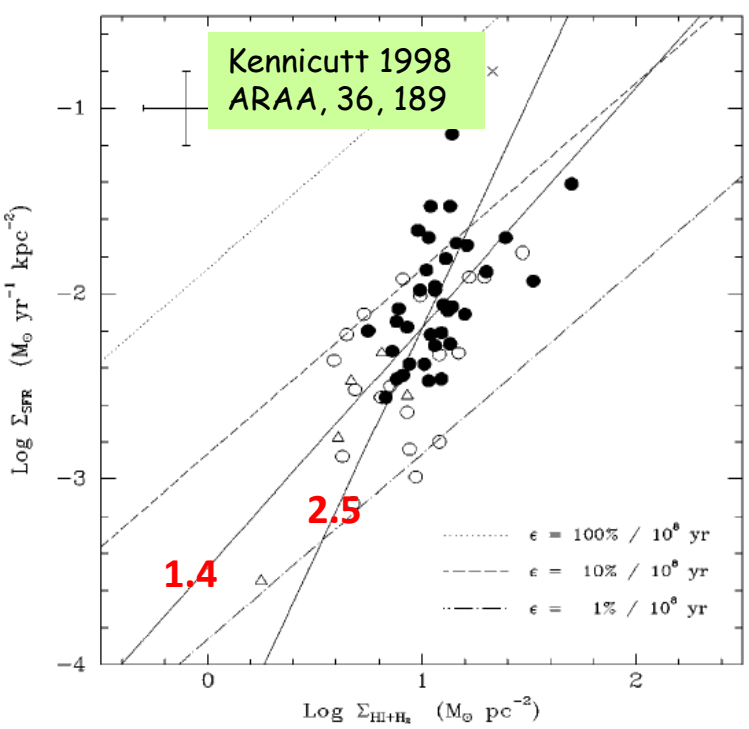
$\propto \nu_{SN} / r_s^3$

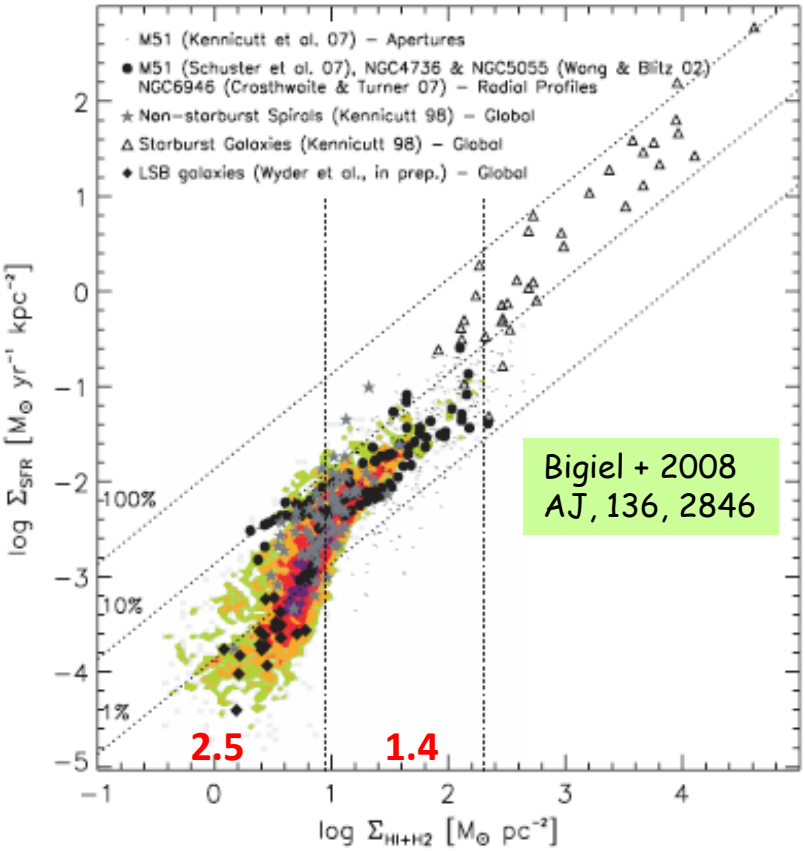
~ const, galaxy-wide

M_H

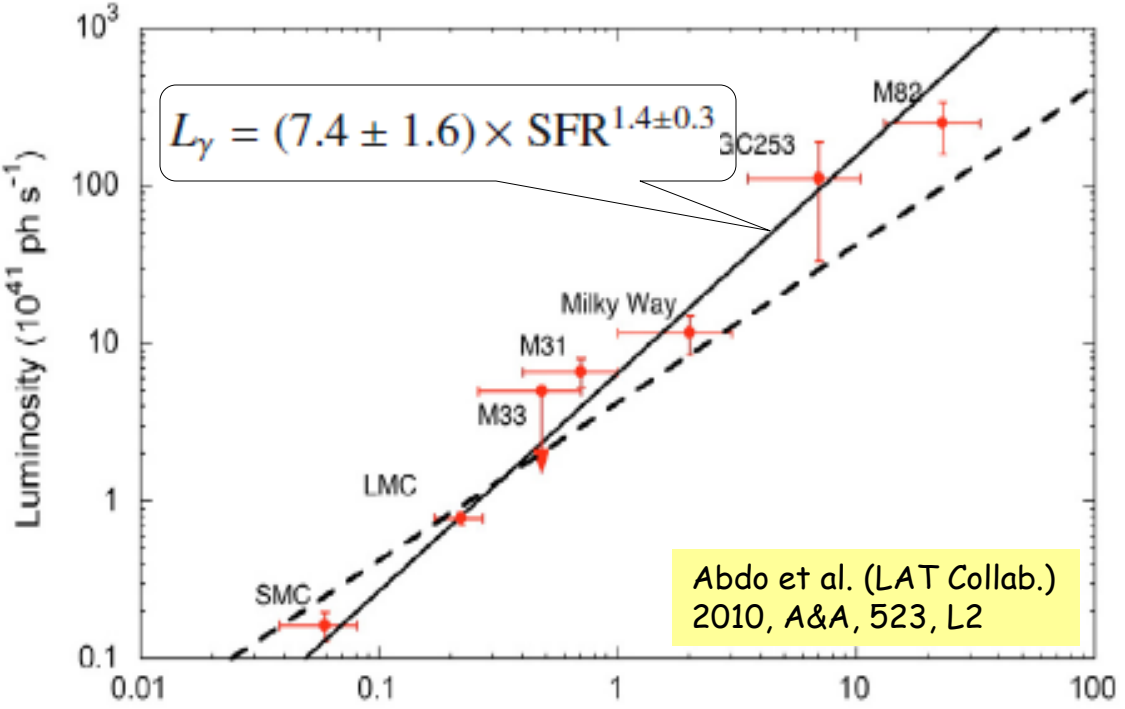


HE emission from star-forming galaxies is mostly **hadronic**





Bigiel + 2008
AJ, 136, 2846



Abdo et al. (LAT Collab.)
2010, A&A, 523, L2

Schmidt-Kennicutt SF law:

$$\Sigma_{SFR} \propto \Sigma_{HI+H_2}^{\alpha}$$

$\alpha \sim 2.5$

$\rightarrow L_\nu \propto \nu_{SN} M_H \propto$

$\mathrm{SFR}\, M_H \propto$

$\mathrm{SFR}^{(1+1/\alpha)} = \mathbf{SFR^{1.4}}$

Measuring CR energy densities (U_p) in galaxies

❶ U_p from γ-ray emission: $L_{\geq\epsilon} = \int_V g_{\geq\epsilon}\, n\, U_p\, dV \quad s^{-1}$

Lifetime for energy gain: $\tau_+ = E/\dot{E} = (\Delta E/E)^{-1}\Delta t = \beta^{-1}\,\Delta t \sim 10^5$ yr

Residency lifetime: $\tau_-^{-1} = \tau_{out}^{-1} + \tau_{pp}^{-1}$

M82: $\tau_{out} = 3\times10^4$ yr

$$\tau_{out} = 3 \times 10^4 \left(\frac{r_s}{0.3\,\mathrm{kpc}}\right)\left(\frac{v_{out}}{2500\,\mathrm{km\,s^{-1}}}\right)^{-1} \mathrm{yr}$$

$$\tau_{pp} \sim 2 \times 10^7 n_p^{-1}\ \mathrm{yr}$$

M82: $\tau_{pp} = 2\times10^5$ yr

Starburst lifetime: $\tau_{SB} \sim \tau_{dyn} \sim 10^8$ yr

$\tau_+ \sim \tau_- \sim 10^5$ yr $<<$ τ_{SB}

Balance of gains vs losses achieved during SB

Equilibrium: min-energy confuguration → CR vs B equipartition

p/e ratio → ❷ U_p from (radio synchrotron em. of) CRe

❸ U_p from SN rate & residency time: $U_p \propto \nu_{SN}\,\tau_-$

Arp 220	→	$U_p \approx$ 475	eV cm^{-3}	*radio*
NGC 253	→	125		*radio*, γ
M 82	→	111		*radio*, γ
Milky Way	→	1		…
M31	→	0.35		γ
LMC	→	0.25		γ
SMC	→	0.15		γ

U_p from supernovae

- massive star formation → SN
- SNR → Fermi-I mechanism → CR
- CR – SN relation (Ginzburg & Syrovatskii 1964)

observed — Milky Way normalization — observed

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

Arp 220	→	$U_p \approx$ **476** eV cm^{-3}
NGC 253	→	**125**
M 82	→	**111**
Milky Way	→	**1**
M31	→	**0.35**
LMC	→	**0.25**
SMC	→	**0.15**

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

SN r… obs'd

particle accel. ef… $\eta \approx 5\%$

SB radiu… obs'd

τ_{-}: protons' lifetime

$E_{ej} \approx 10^{51}$ erg

kin. ene… of SN ejecta

$\tau_{-} \approx$

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

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

	U_p	ν_{SN}	τ_{-}	r_s
Arp 220	**515** eV cm^{-3}	3.50 yr^{-1}	9.0E+3 yr *adv*	0.25 kpc
NGC 253	**77** eV cm^{-3}	0.12 yr^{-1}	2.0E+4 yr *adv*	0.20 kpc
M 82	**95** eV cm^{-3}	0.25 yr^{-1}	2.6E+3 yr *adv*	0.26 kpc
MW	**1.8** eV cm^{-3}	0.02 yr^{-1}	5.0E+6 yr *pp*	2.4 kpc
M31	**0.7** eV cm^{-3}	0.01 yr^{-1}	2.0E+7 yr *pp*	4.2 kpc
LMC	**0.2** eV cm^{-3}	2 E-3 yr^{-1}	1.0E+7 yr *pp*	3.0 kpc
SMC	**1.0** eV cm^{-3}	1 E-3 yr^{-1}	4.0E+7 yr *pp*	2.1 kpc

if CRp advected by diffusion v_{diff}=100 km/s → U_p=0.15 eV/cm^3

CONCLUSIONS on CRs

U_p can be measured from:

i) γ-ray emission (directly)

ii) radio synchrotron emission (indirectly), assuming p/e ratio, part./field equilibrium.

iii) SN rates and CRp lifetimes.

Starbursts: $U_p \sim O(100)$ eV cm^{-3}

Quiet SFGs: $U_p \sim O(1)$ eV cm^{-3}

Universal(?) acceleration efficiency of SN.

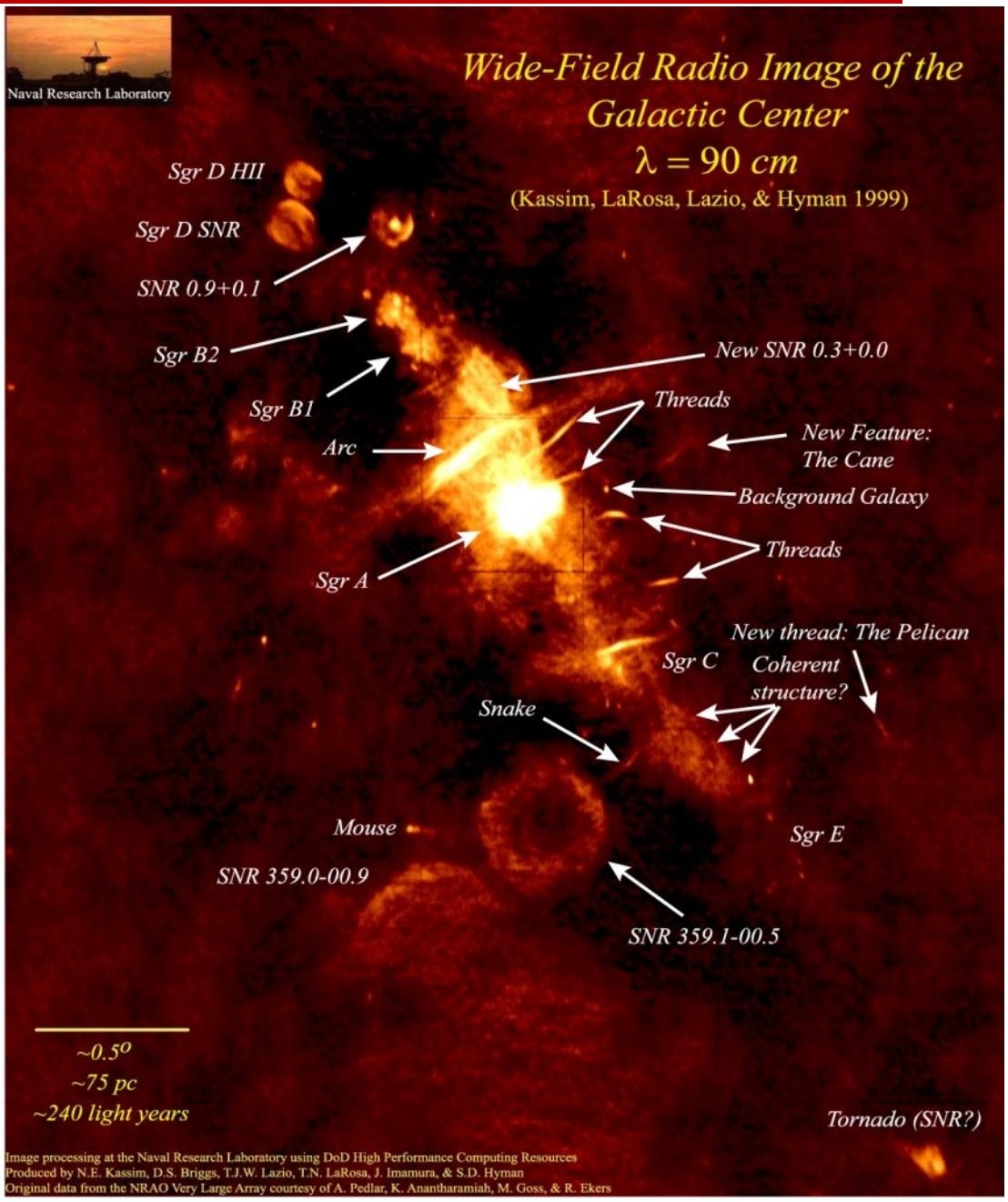
Fermi I acceleration at work (NR strong shock).

Particles/field equipartition in place.

→ radio data to study CRs in high-z SFGs

Happy ending?

Targets for DM search



Requirements:

1. Not associated with known conventional TeV sources
2. High DM density
3. Close by
4. Not extended

1. Galactic Center

Distance ~ 7.5 kpc → OK

... but:

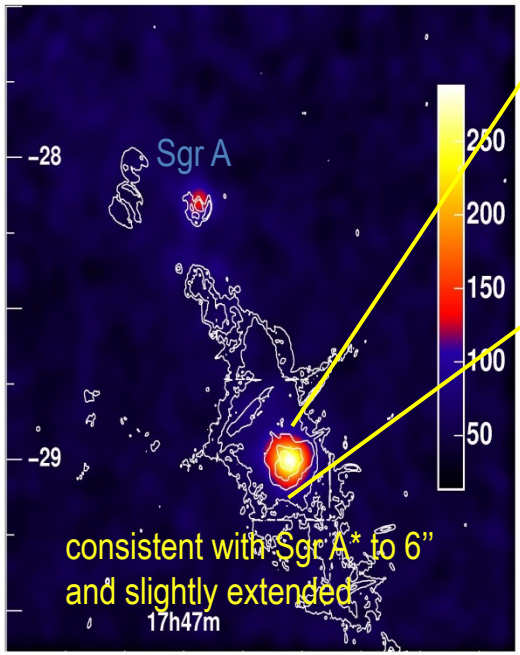
other γ-ray sources in the FOV, i.e. SNR Sgr A East

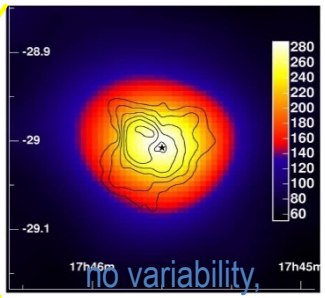
→ plausible competing scenarios

2. Dwarf Sph galaxies

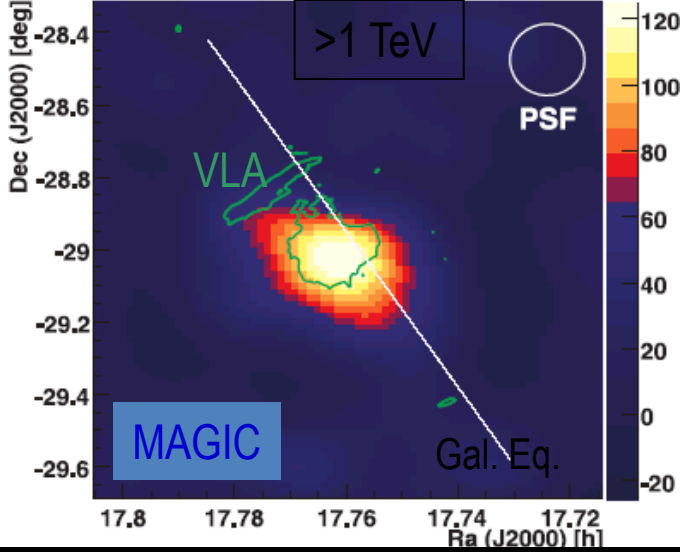
ok 1(?), 2, 3, 4

1. The Galactic Center

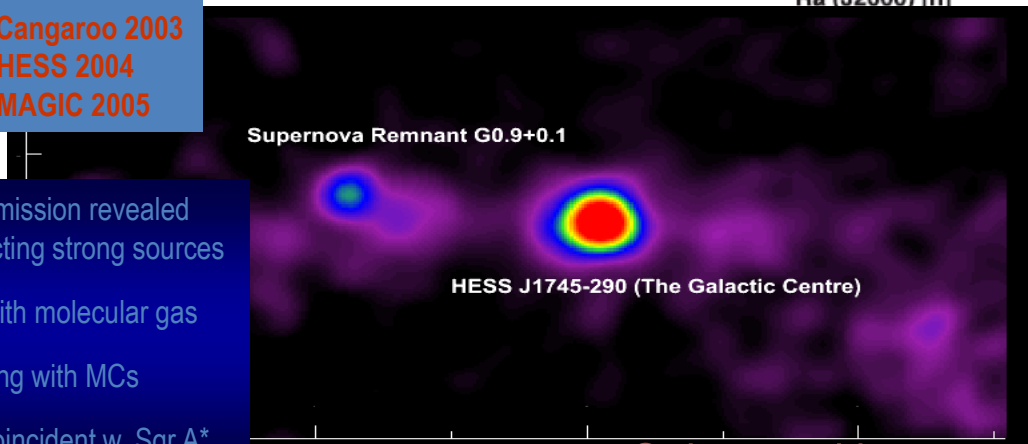




no variability,
yr-min scale



Detected: **Cangaroo 2003**
Confirmed: **HESS 2004**
Confirmed: **MAGIC 2005**

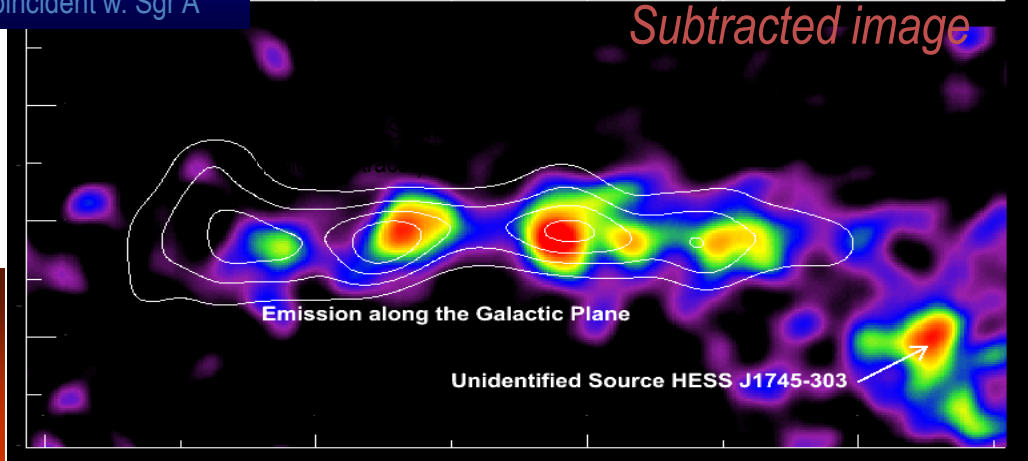


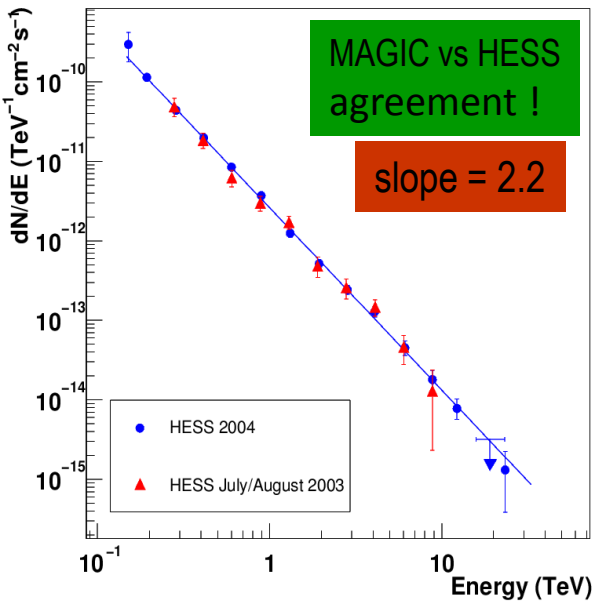
Diffuse GP emission revealed
by subtracting strong sources

Correlation with molecular gas

CRs interacting with MCs

GC source coincident w. Sgr A*





GC signal: unlikely to be DM

Some background on galaxy structure ..

$$I(r) = I_0 \exp(-r/R_d)$$

same profile at all luminosities!

1000 galaxies
Persic + 1996

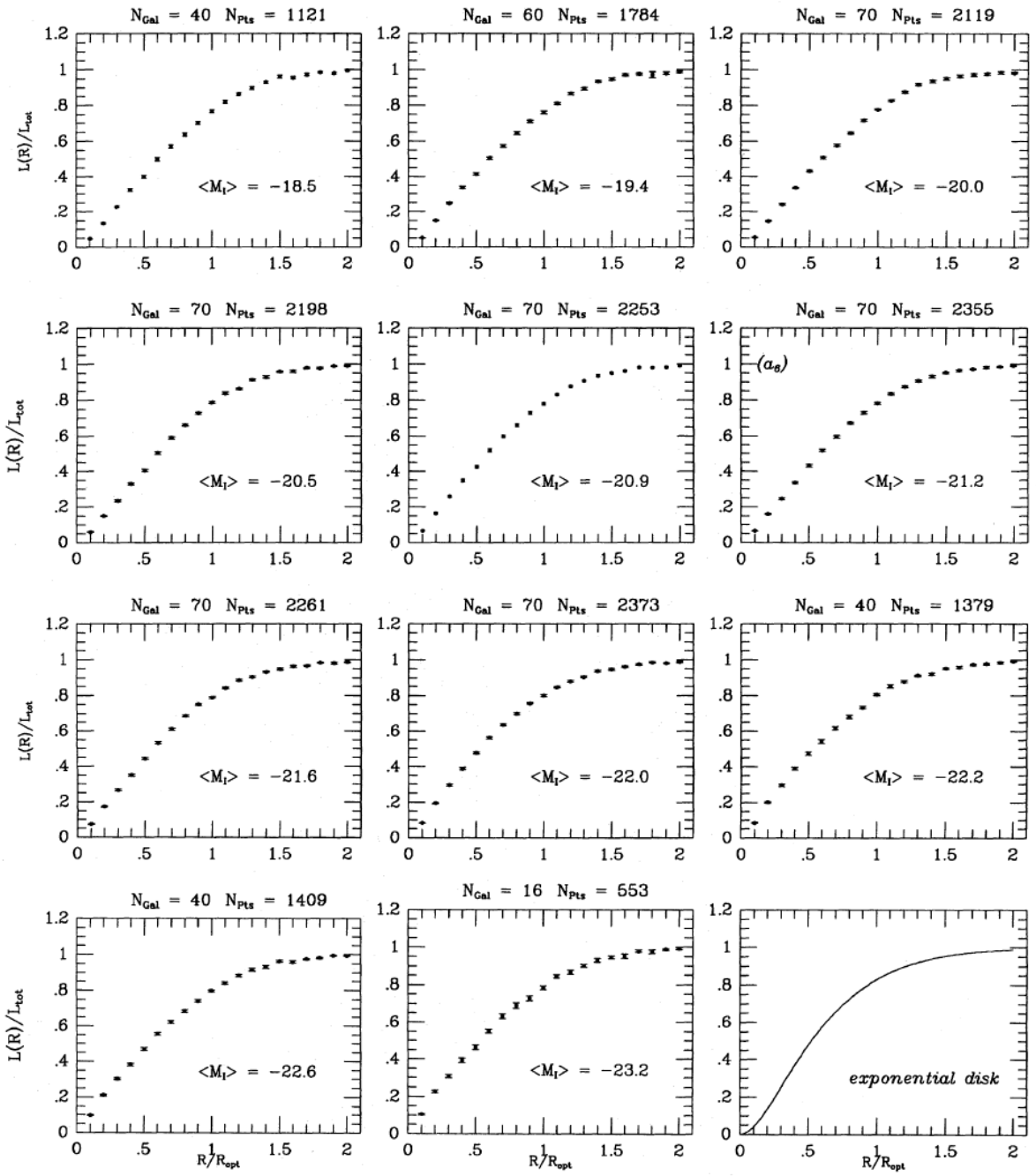


Figure A1. The luminous mass profiles for the galaxies in Sample B, grouped by luminosity bins. For each individual object, the light profile $L(r) \propto \int_0^r I(r')\, r'\, dr'$ is normalized to its total value L_∞; the radius is normalized to R_{opt}. Grouping the light profiles by velocity amplitude yields a similar result.

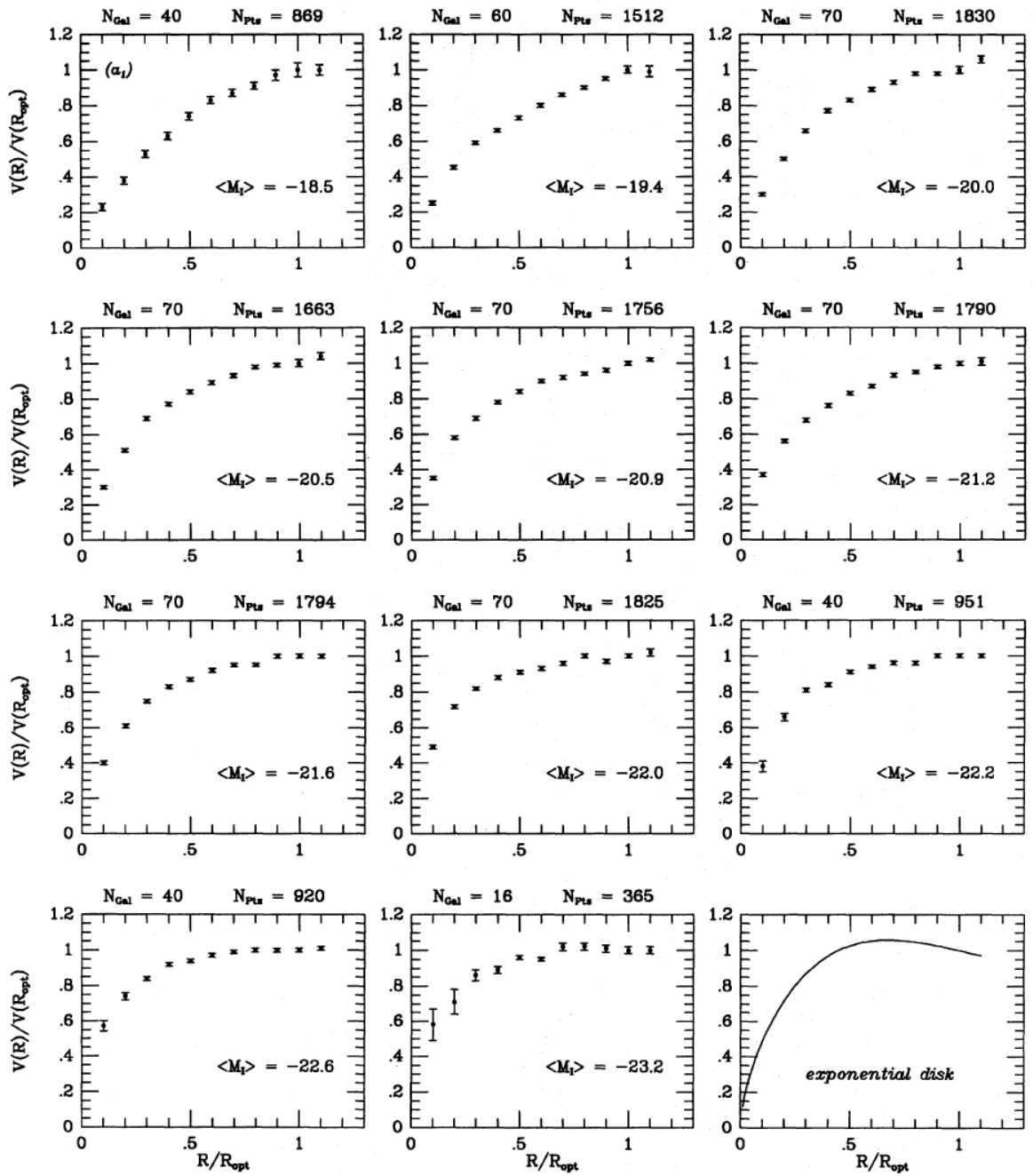
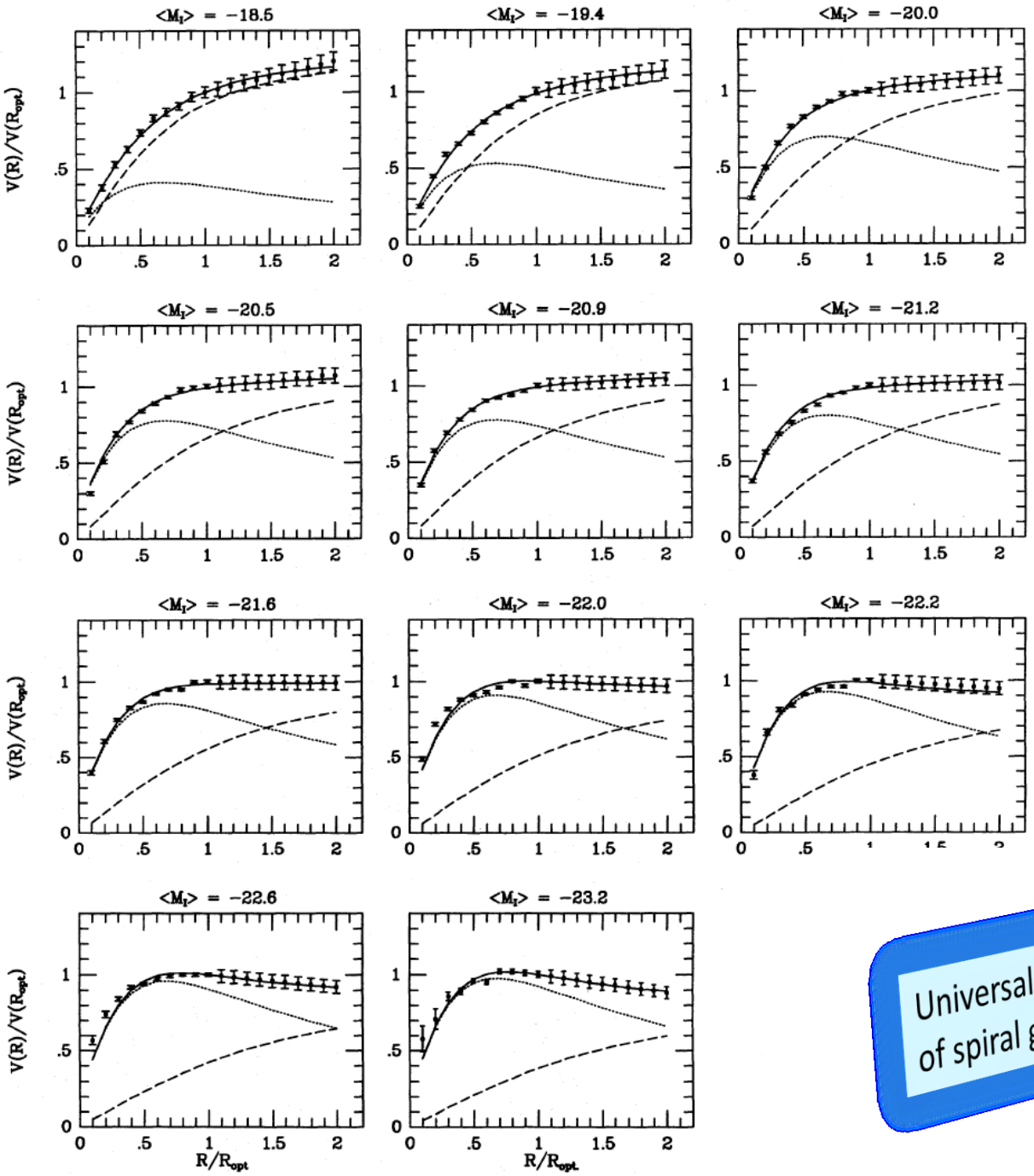


Figure 1. Synthetic rotation curves for Sample B arranged by luminosity. Galactocentric radii are normalized to R_{opt}, the radius encompassing 83 per cent of the total I luminosity. The last panel shows the rotation curve predicted for a pure self-gravitating exponential thin disc.

Rotation curves are **not** self-similar with luminosity!



Smooth progression of RC shape, and disk/halo interplay, with luminosity

Universal Rotation Curve of spiral galaxies

Figure 6. Best two-component fits to the universal rotation curve (dotted line: disc; dashed line: halo)

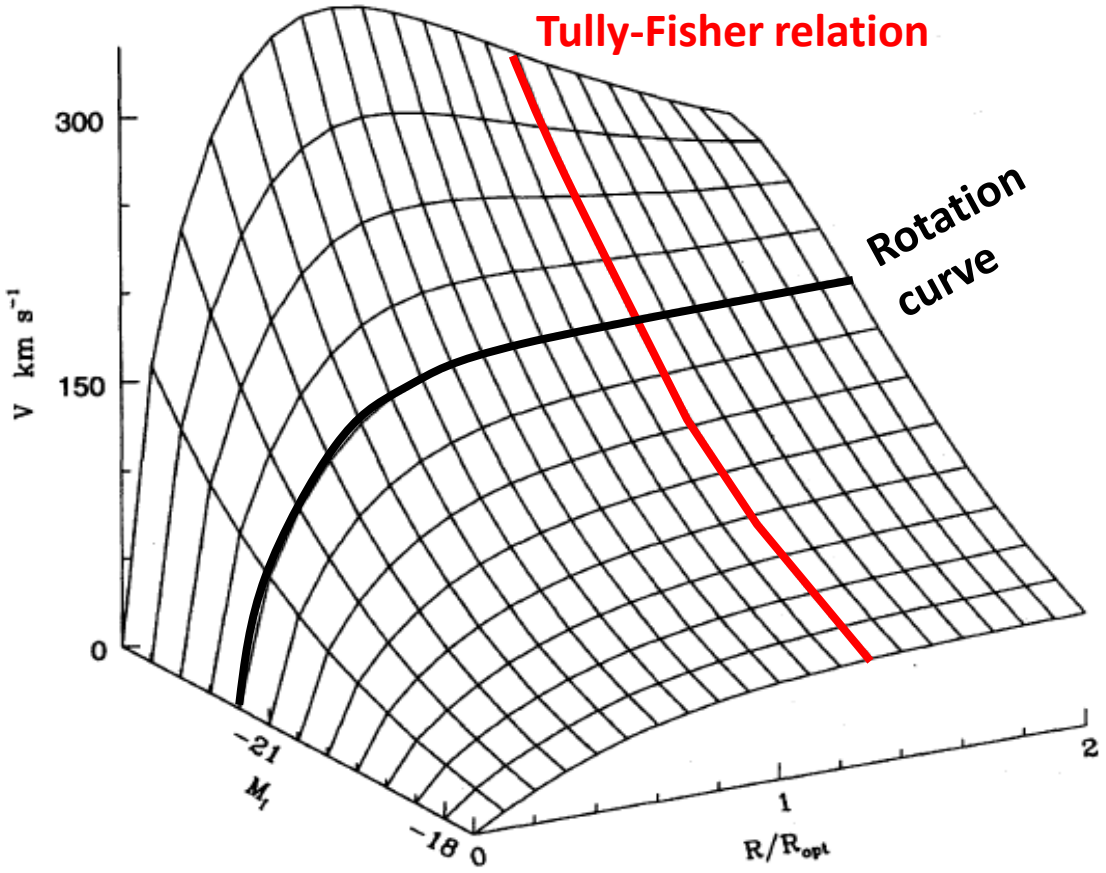
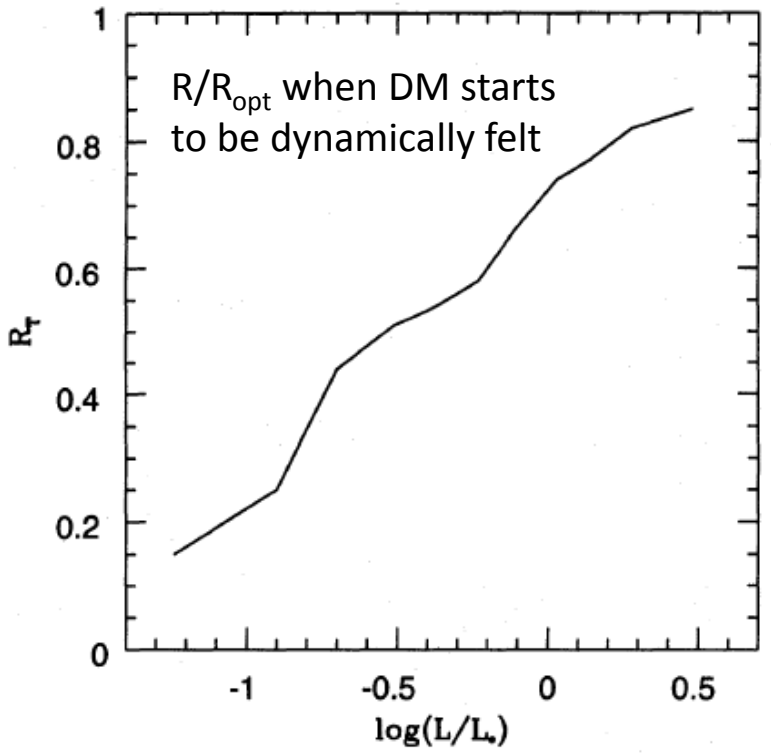


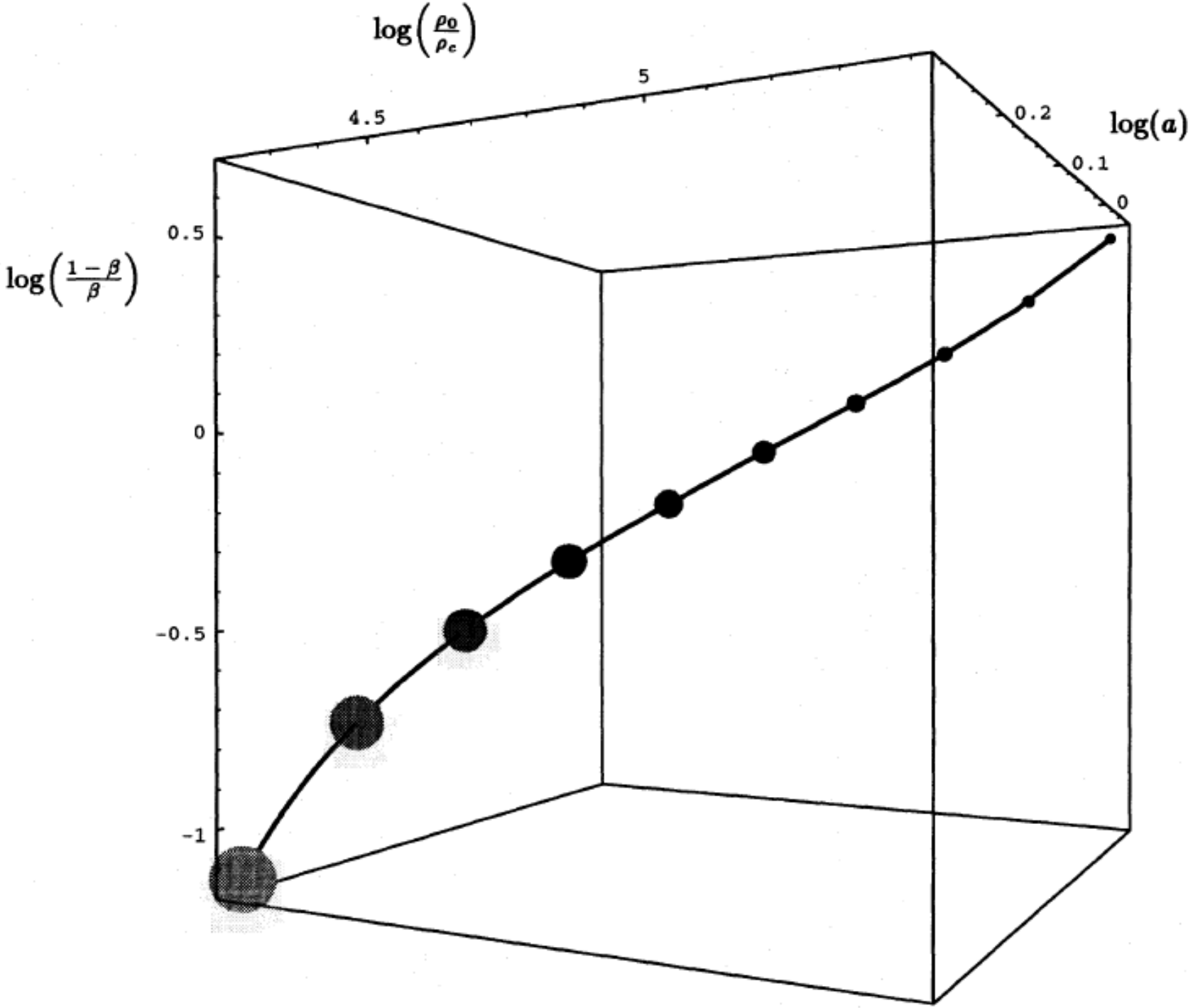
Figure 10. The URC surface.



$$\frac{\text{dark mass}}{\text{visible mass}} = 0.4\left(\frac{L}{L_*}\right)^{-0.9}$$

$$\text{halo mass} = 1.6\times 10^{12}\left(\frac{L}{L_*}\right)^{0.56} \mathrm{M}_\odot$$

$$\frac{\text{halo central density}}{\text{critical density}} = 3.5\times 10^{4}\left(\frac{L}{L_*}\right)^{-0.7}$$


$\log\left(\frac{\rho_0}{\rho_c}\right)$
5
4.5
0.2
$\log(a)$
0.1
0
0.5
$\log\left(\frac{1-\beta}{\beta}\right)$
0
-0.5
-1

Whence these properties?

- Bottom-up cosmology: small galaxies formed first, hence their density retains the cosmological density at the epch of their turnaround ($\delta\rho/\rho \sim 1.8$).

- Baryon infall: SF → SN expl. → winds → most of infalling baryons **lost** in small gals., but **retained** in bigger ones.

- Smaller, denser gals. have little/no SF – bigger, less dense gals. do have gas and SF.

Small, nearby galaxies … or … large, faraway clusters?

Let's start from signal from self-interacting DM decay

$$\Phi_\epsilon^{PP}(>E_0) = \frac{1}{4\pi}\frac{\langle\sigma_{\rm ann}v\rangle}{2m_\chi^2}\int_{E_0}^{m_\chi}\sum_{i=1}^{n}B^i\frac{dN_\gamma^i}{dE}\,dE$$

$$\Phi(>E_0,\Delta\Omega) = \Phi_\epsilon^{PP}(>E_0)\;J\,(\Delta\Omega)\;D^{-2}$$

→ small distances best!

$$J(\Delta\Omega) = \int_{\Delta\Omega}\int_{los}\rho^2(r(s,\Omega))\,ds\,d\Omega$$

→ small guys win!

→ cosmology: dSph **halos** are best candidates for DM signal

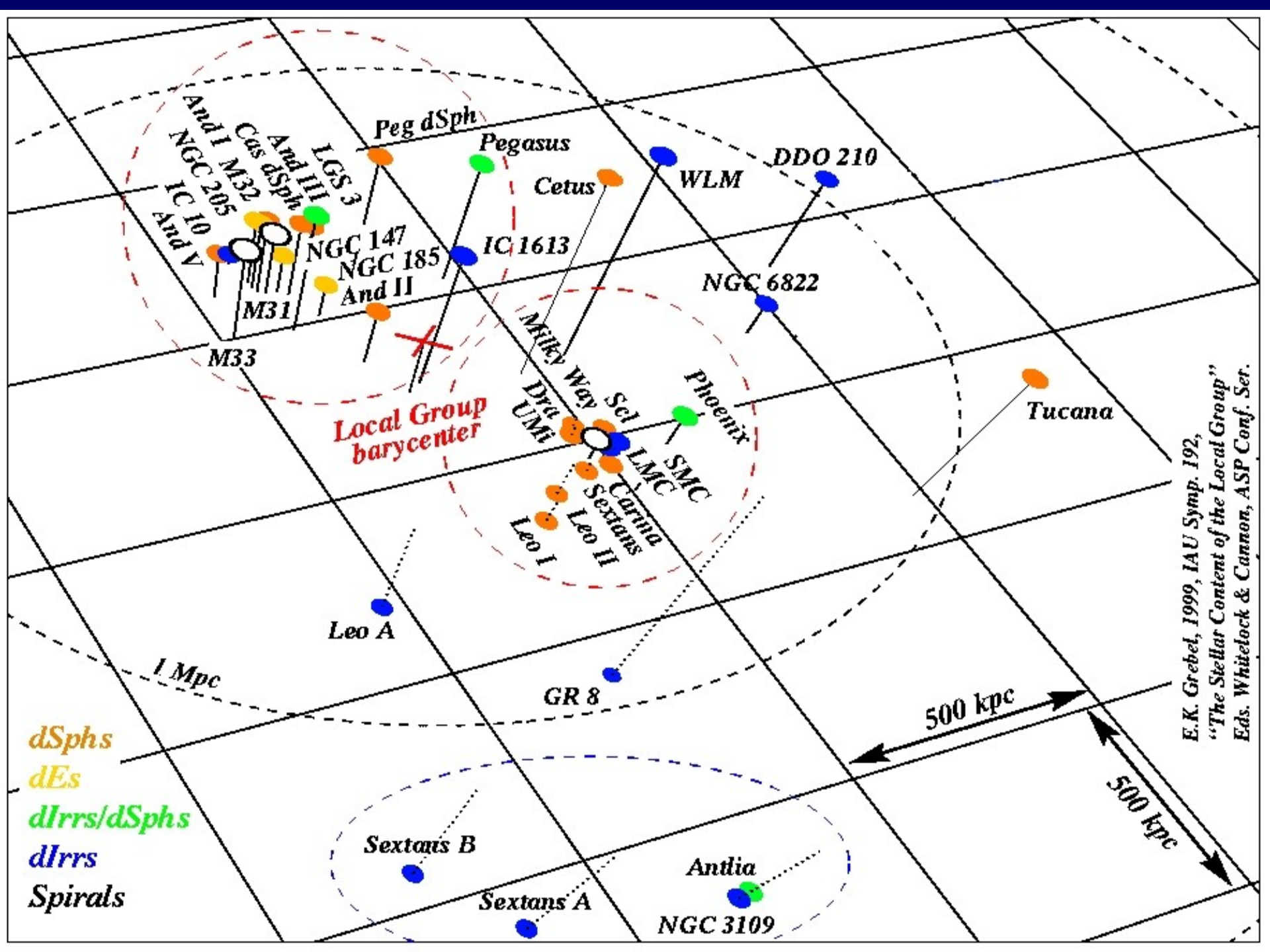
→ astrophysics: dSph **stellar pops**. are most silent astroph bkgd

→ Dwarf Spheroidals: ideal DM candidates

Milky Way satellites → **nearby**
High M/L → **DM dominated**
Old stellar pop. → **no ongoing SF**

DSph	$D_\odot$ (kpc)	L (10^3 $L_\odot$)	M/L ratio	Reference	Best positioned IACTs
Carina	101	430	40	[10]	HESS, CANGAROO
Draco	82	260	320	[10]	**MAGIC**, VERITAS
Fornax	138	15500	10	[10]	HESS, CANGAROO
Sculptor	79	2200	7	[10]	HESS, CANGAROO
Sextans	86	500	90	[10]	HESS, CANGAROO
UMi	66	290	580	[10]	**MAGIC**, VERITAS
Sagittarius*	24	58000	25	[10, 11]	HESS, CANGAROO
Coma Berenices	44	2.6	450	[12]	**MAGIC**, VERITAS
UMa II	32	2.8	1100?	[12]	**MAGIC**, VERITAS
Willman 1	38	0.9	700	[12]	**MAGIC**, VERITAS
Segue 1†	23	0.3	>1320	[13]	**MAGIC**, VERITAS

* Not a dSph, but listed here because of its traditional interest for DM searches.


Peg dSph
Pegasus
Cetus
WLM
DDO 210
And I
M32
Cas dSph
And III
LGS 3
NGC 205
IC 10
And V
NGC 147
NGC 185
And II
IC 1613
M31
M33
NGC 6822
Milky Way
Local Group
barycenter
Dra
UMi
Scl
Phoenix
Tucana
SMC
LMC
Carina
Sextans
Leo II
Leo I
Leo A
1 Mpc
GR 8
500 kpc
500 kpc
dSphs
dEs
dIrrs/dSphs
dIrrs
Spirals
Sextans B
Antlia
Sextans A
NGC 3109
E.K. Grebel, 1999, IAU Symp. 192,
"The Stellar Content of the Local Group"
Eds. Whitelock & Cannon, ASP Conf. Ser.

Example: Draco dSph modeling

d~80 kpc

Bergström & Hooper 2006

total DM annihil. rate

$$\Phi_A = \int_{r_{min}}^{r_a} dr\, 4\pi r^2 \frac{\langle \sigma_A v \rangle}{2} \left(\frac{\rho(r)}{m_\chi} \right)^2$$

<σ_A v>, m_χ WIMP annihil. cross section, mass

γ-ray flux

$$F_\gamma = \frac{\Phi_A N_\gamma}{4\pi D^2}$$

N_γ γ rays / annihil

$$y = r/r_s$$

upper limit

cusped profile

$$\rho(r) = \frac{\rho_0}{y\,(1+y)^2}$$

$$F_\gamma = \frac{\rho_0^2 r_s^3 N_\gamma}{3 m_\chi^2 D^2} \frac{\langle \sigma_A v \rangle}{2} \left[\frac{1}{(1+y_{min})^3} - \frac{1}{(1+y_a)^3} \right]$$

cored profile

$$\rho(r) = \frac{\rho_0}{(1+y)\,(1+y^2)}$$

$$F_\gamma = \frac{\rho_0^2 r_s^3 N_\gamma}{4 m_\chi^2 D^2} \frac{\langle \sigma_A v \rangle}{2} \left[\frac{2 + y_{min} + y_{min}^2}{1 + y_{min} + y_{min}^2 + y_{min}^3} + \arctan(y_{min}) - \frac{2 + y_a + y_a^2}{1 + y_a + y_a^2 + y_a^3} - \arctan(y_a) \right]$$

γ-ray flux

$$F_\gamma = \frac{\rho_0^2 r_s^3 N_\gamma}{3 m_\chi^2 D^2} \frac{\langle \sigma_A v \rangle}{2} \times A$$

part. phys

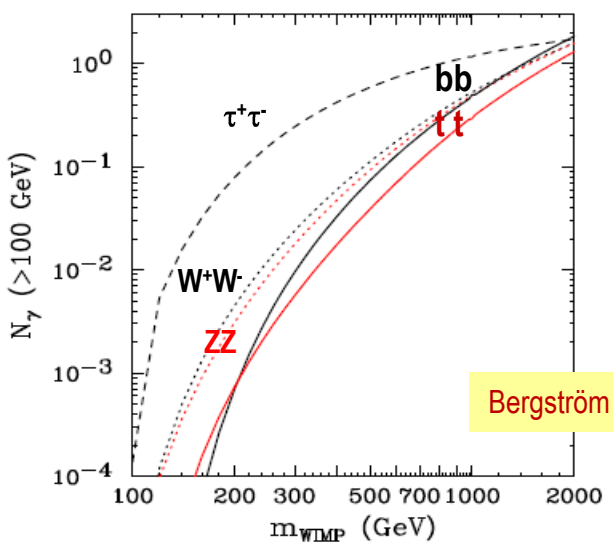
astrophys

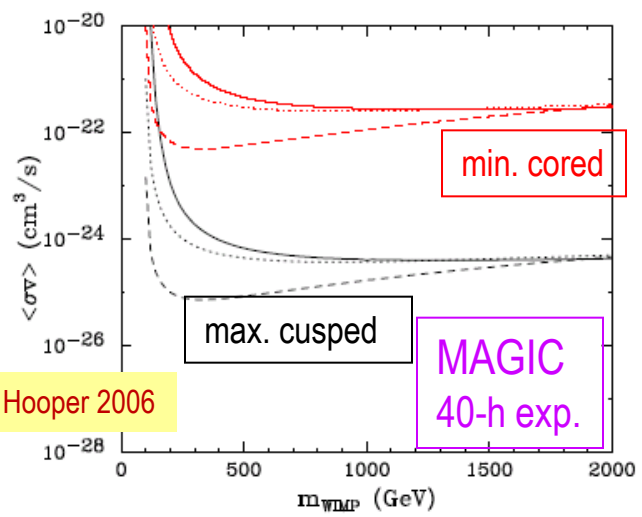
Profile Type	$A(r_a = r_s)$	$A(r_a \gg r_s)$
NFW	0.875	1.0
Core	0.160	0.323
Cusp, $\gamma = 1.1$	1.29	1.52
Cusp, $\gamma = 1.2$	2.16	2.63
Cusp, $\gamma = 1.3$	4.03	4.12
Cusp, $\gamma = 1.4$	11.1	12.5
Cusp, $\gamma = 1.45$	25.7	27.4

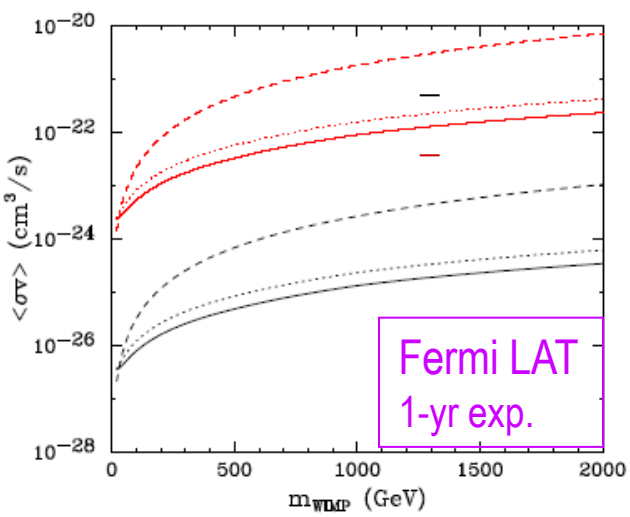
r_s = 7 – 0.2 kpc

$\rho_0 = 10^7 – 10^9\ M_\odot\ kpc^{-3}$

$\rho_0^2\, r_s^3 = 0.03 – 6\ M_\odot^2\ kpc^{-3}$







Bergström & Hooper 2006

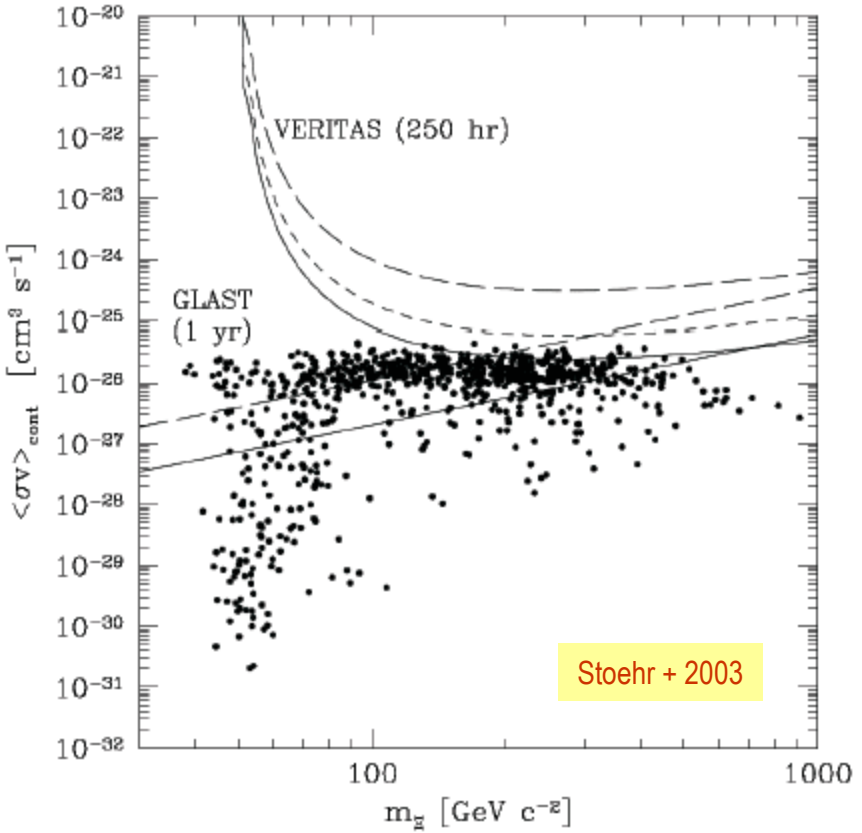
$$F^{\max}_{\gamma,\mathrm{NFW}} \approx 2.4\times10^{-10}\left(\frac{100\ \mathrm{GeV}}{m_\chi}\right)^2\left(\frac{\langle\sigma_A v\rangle}{3\cdot10^{-26}\ \mathrm{cm^3 s^{-1}}}\right)\left(\frac{N_\gamma}{10}\right)\mathrm{cm^{-2}s^{-1}}$$

$$F^{\min}_{\gamma,\mathrm{NFW}} \approx 9.8\times10^{-13}\left(\frac{100\ \mathrm{GeV}}{m_\chi}\right)^2\left(\frac{\langle\sigma_A v\rangle}{3\cdot10^{-26}\ \mathrm{cm^3 s^{-1}}}\right)\left(\frac{N_\gamma}{10}\right)\mathrm{cm^{-2}s^{-1}}$$

$$F^{\max}_{\gamma,\mathrm{core}} \approx 4.2\times10^{-11}\left(\frac{100\ \mathrm{GeV}}{m_\chi}\right)^2\left(\frac{\langle\sigma_A v\rangle}{3\cdot10^{-26}\ \mathrm{cm^3 s^{-1}}}\right)\left(\frac{N_\gamma}{10}\right)\mathrm{cm^{-2}s^{-}}$$

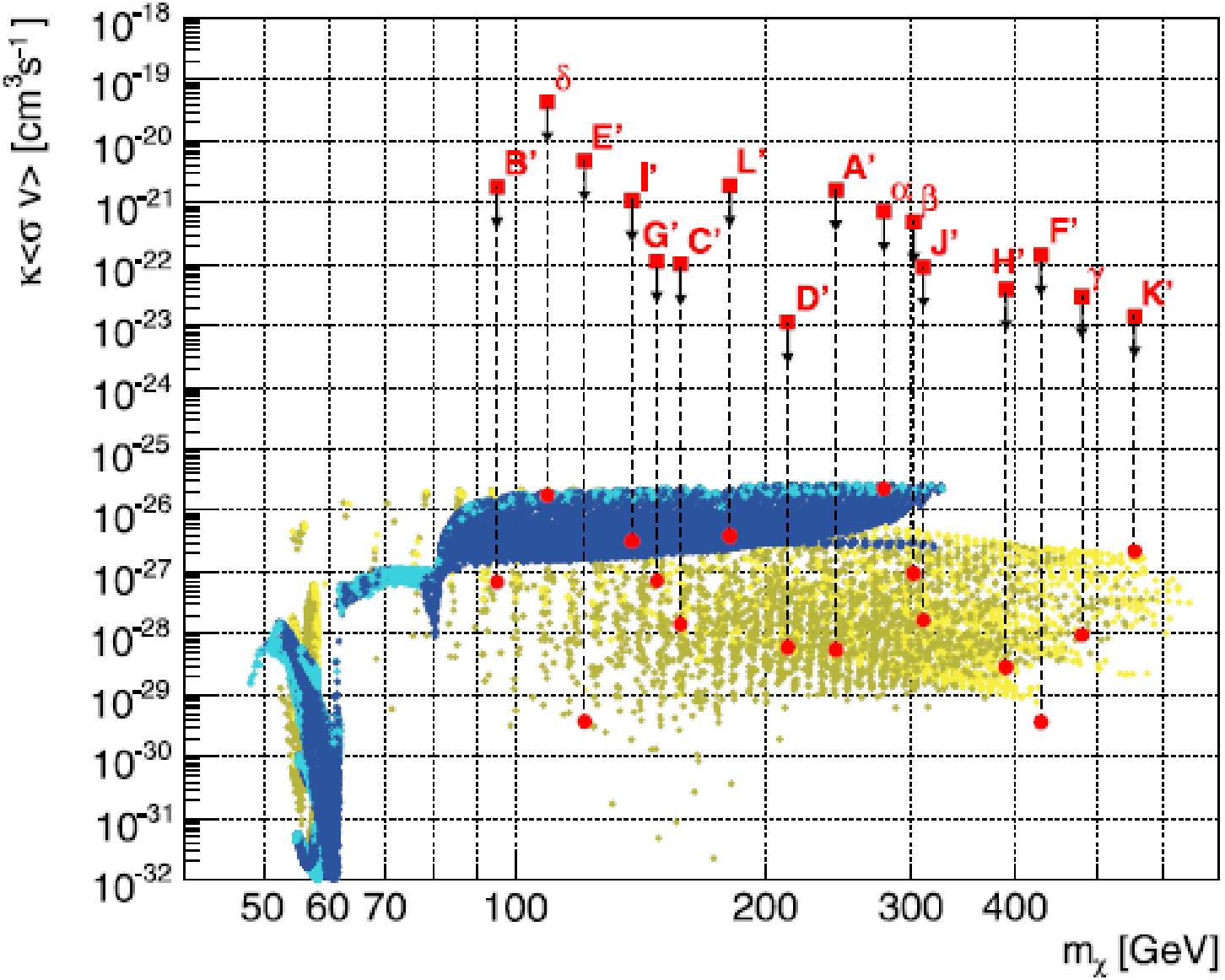
$$F^{\min}_{\gamma,\mathrm{core}} \approx 3.5\times10^{-13}\left(\frac{100\ \mathrm{GeV}}{m_\chi}\right)^2\left(\frac{\langle\sigma_A v\rangle}{3\cdot10^{-26}\ \mathrm{cm^3 s^{-1}}}\right)\left(\frac{N_\gamma}{10}\right)\mathrm{cm^{-2}s^{-}}$$

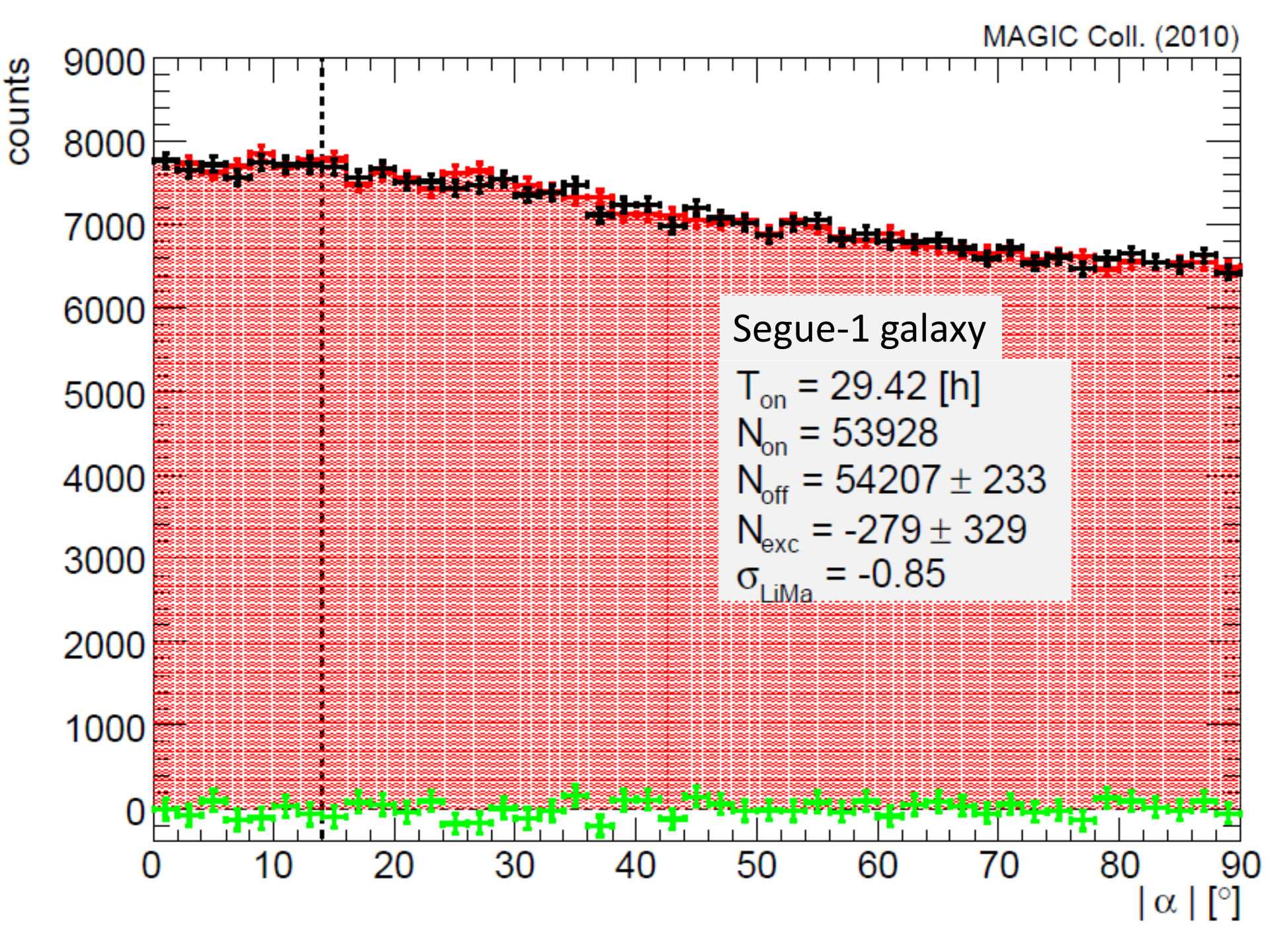
IACT neutralino detection:
$\langle\sigma_A v\rangle \geq 10^{-25}$ cm^{3}s^{-1}



Stoehr + 2003

Draco dSph obs'd MAGIC Albert et al. 2008




MAGIC Coll. (2010)
counts
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
10
20
30
40
50
60
70
80
90
| α | [°]
Segue-1 galaxy
T_on = 29.42 [h]
N_on = 53928
N_off = 54207 ± 233
N_exc = -279 ± 329
σ_LiMa = -0.85

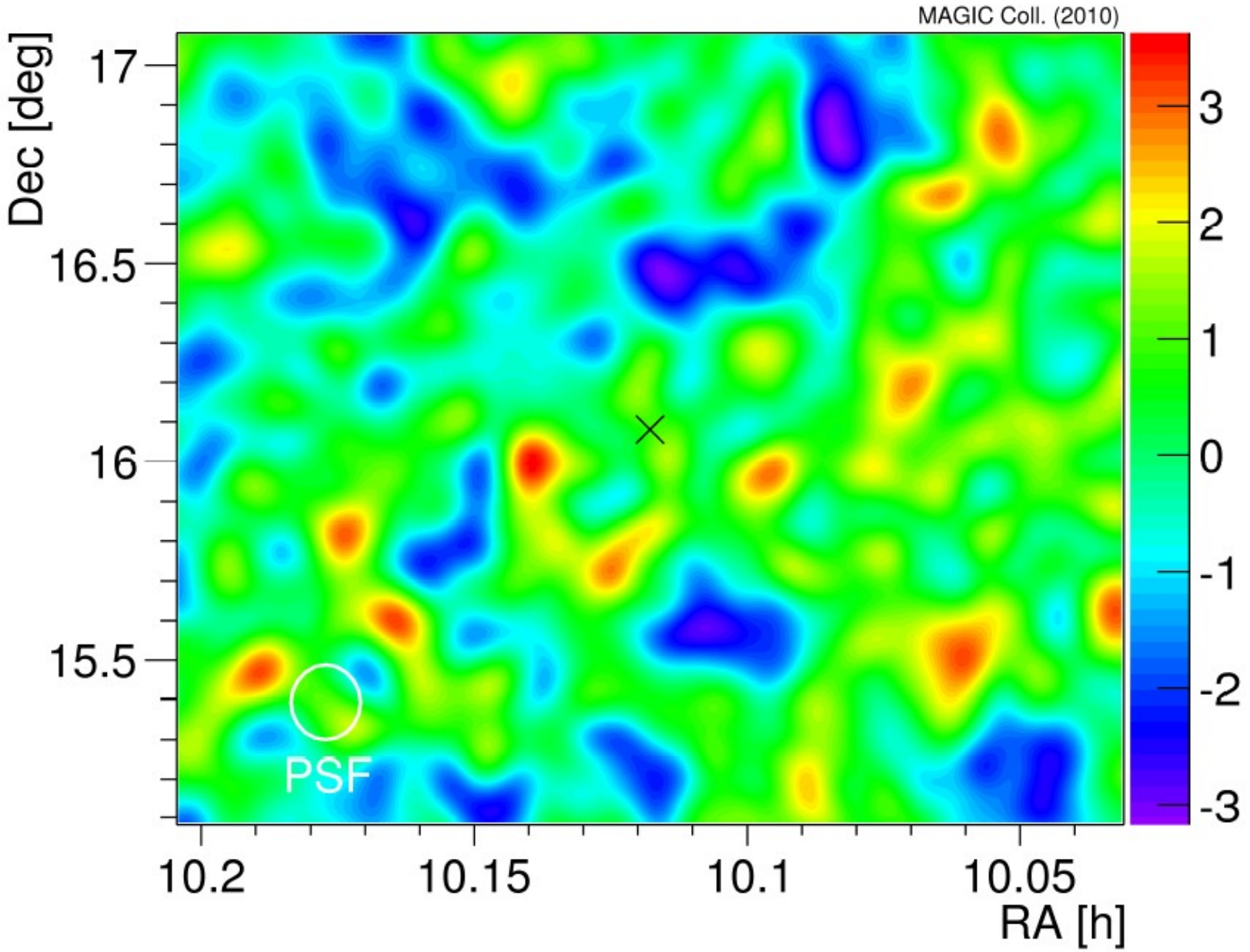
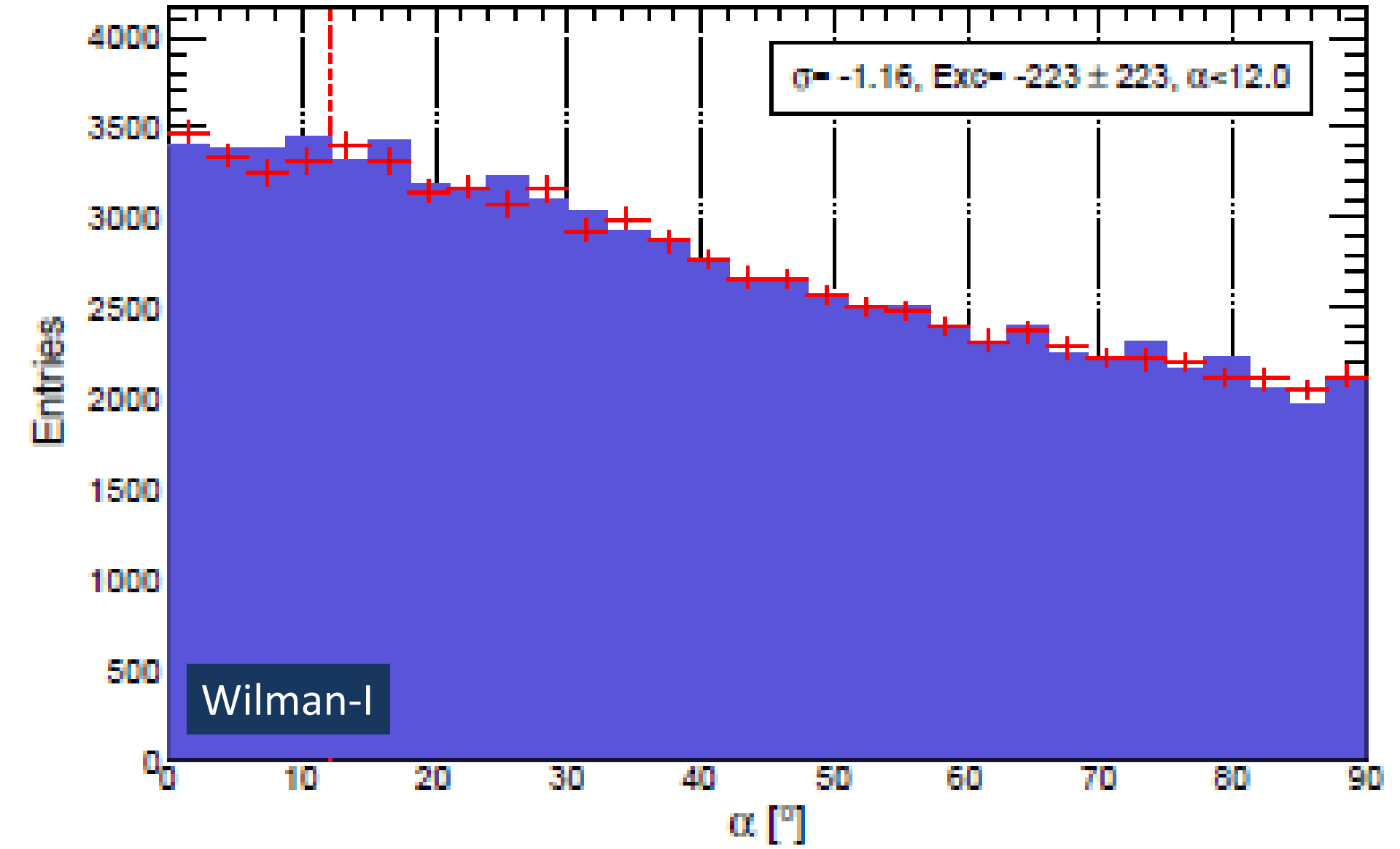


Figure 2. Significance map for events above 200 GeV in the Segue 1 sky region. The black cross marks the position of Segue 1 and the telescope PSF is also shown. The significance distribution is consistent with background fluctuations.


σ= -1.16, Exc= -223 ± 223, α<12.0
Entries
α [°]
Wilman-I
0
500
1000
1500
2000
2500
3000
3500
4000
0
10
20
30
40
50
60
70
80
90

Summary

Galaxies can produce VHE γ rays, related to ongoing SF and DM decay

SF: γ emission detected from nearby starburst (M82, NGC253), quiescent (M31, LMC, SMC), and SB/Seyfert-I (NGC1068, NGC4945) galaxies.
CR energy densities: measured directly from γ emission and indirectly from radio emission, estimated from SR frequencies
→ results agree.

DM: no signal from MW center and from (best candidate) MW satellite dSph galaxies.
→ hunt ongoing ...