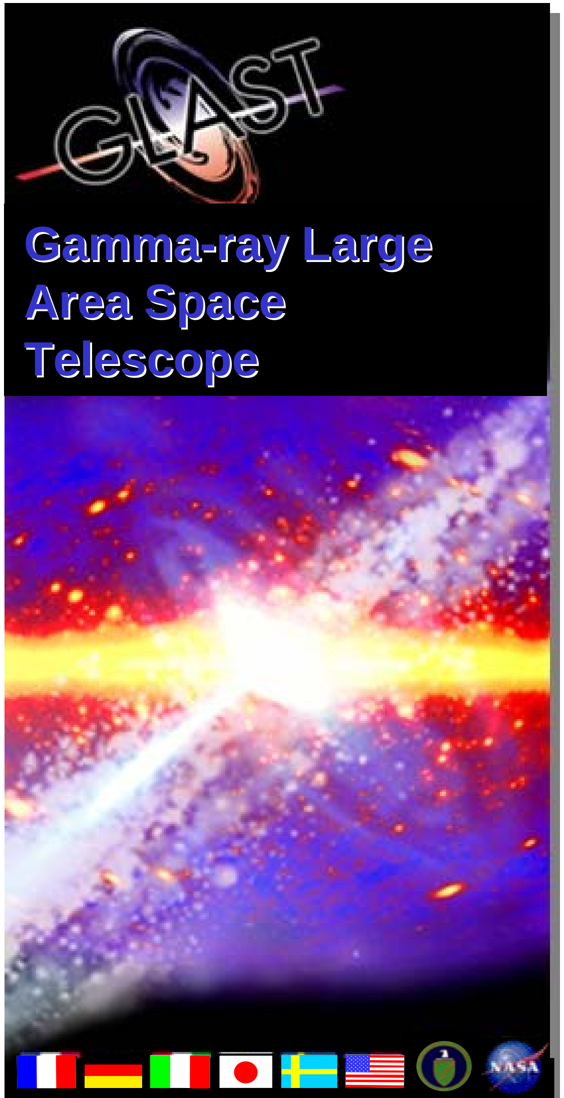
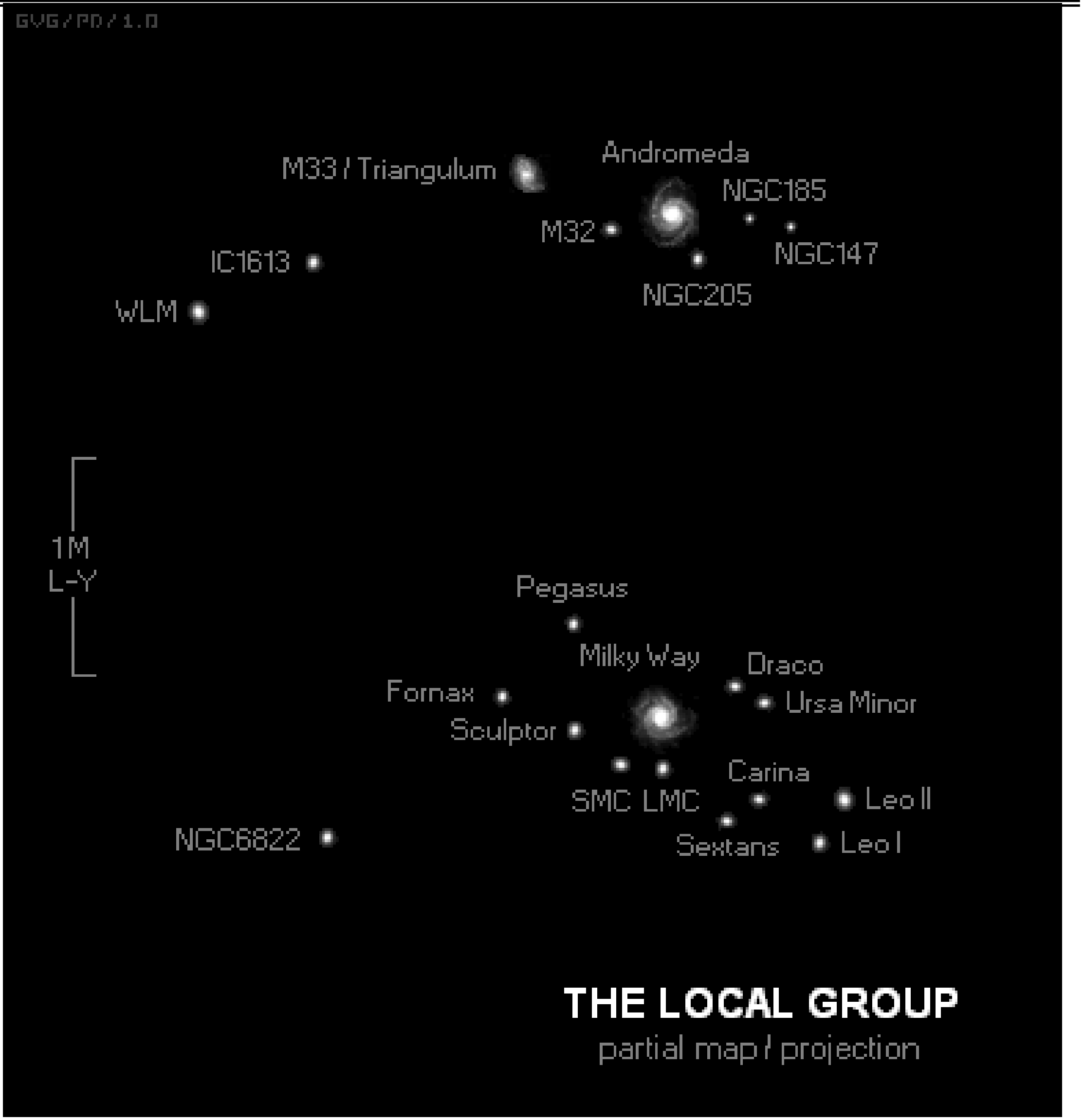


Local Group of Galaxies in the EGRET era and perspectives for GLAST

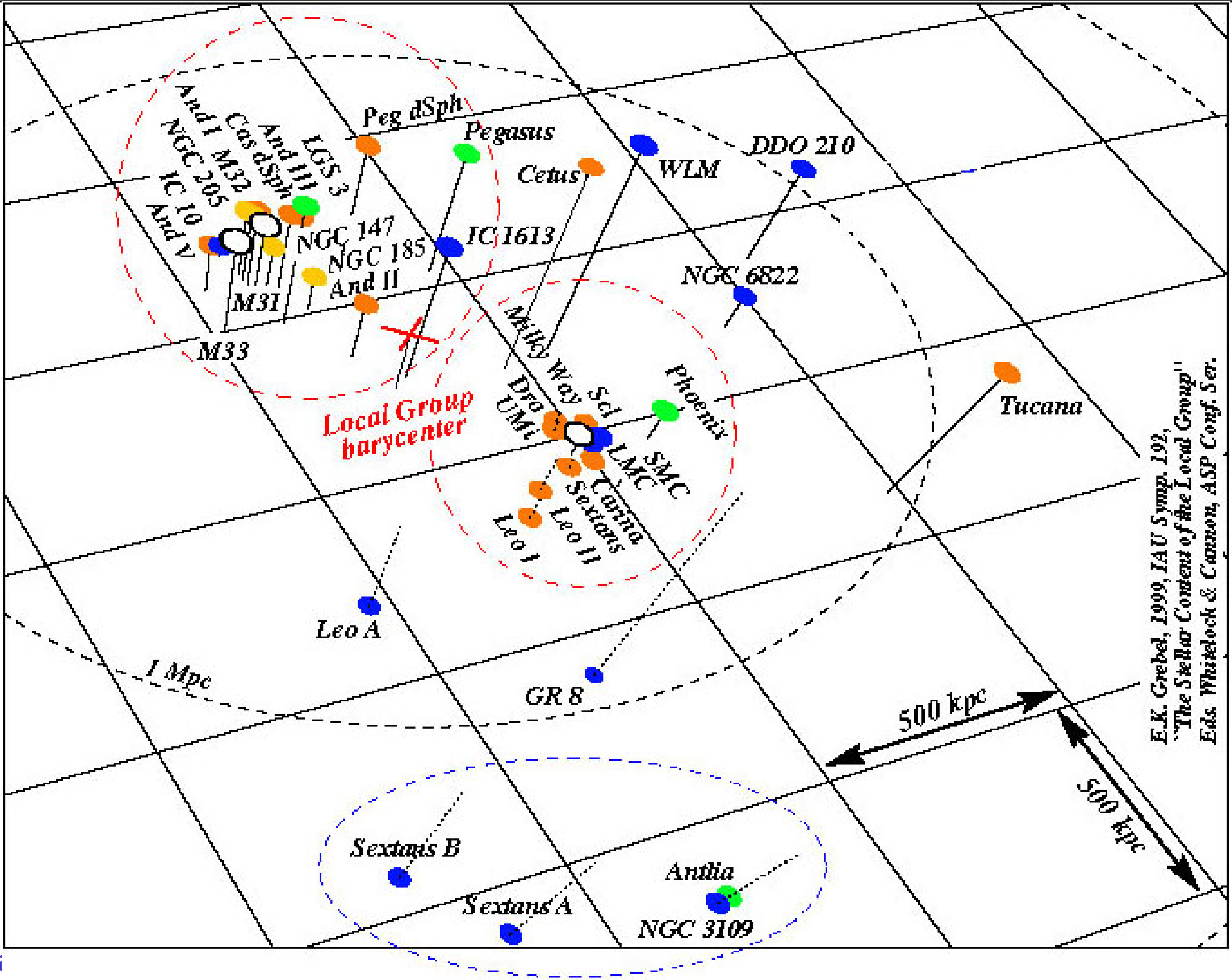
Igor V. Moskalenko
Stanford

Local Group of Galaxies

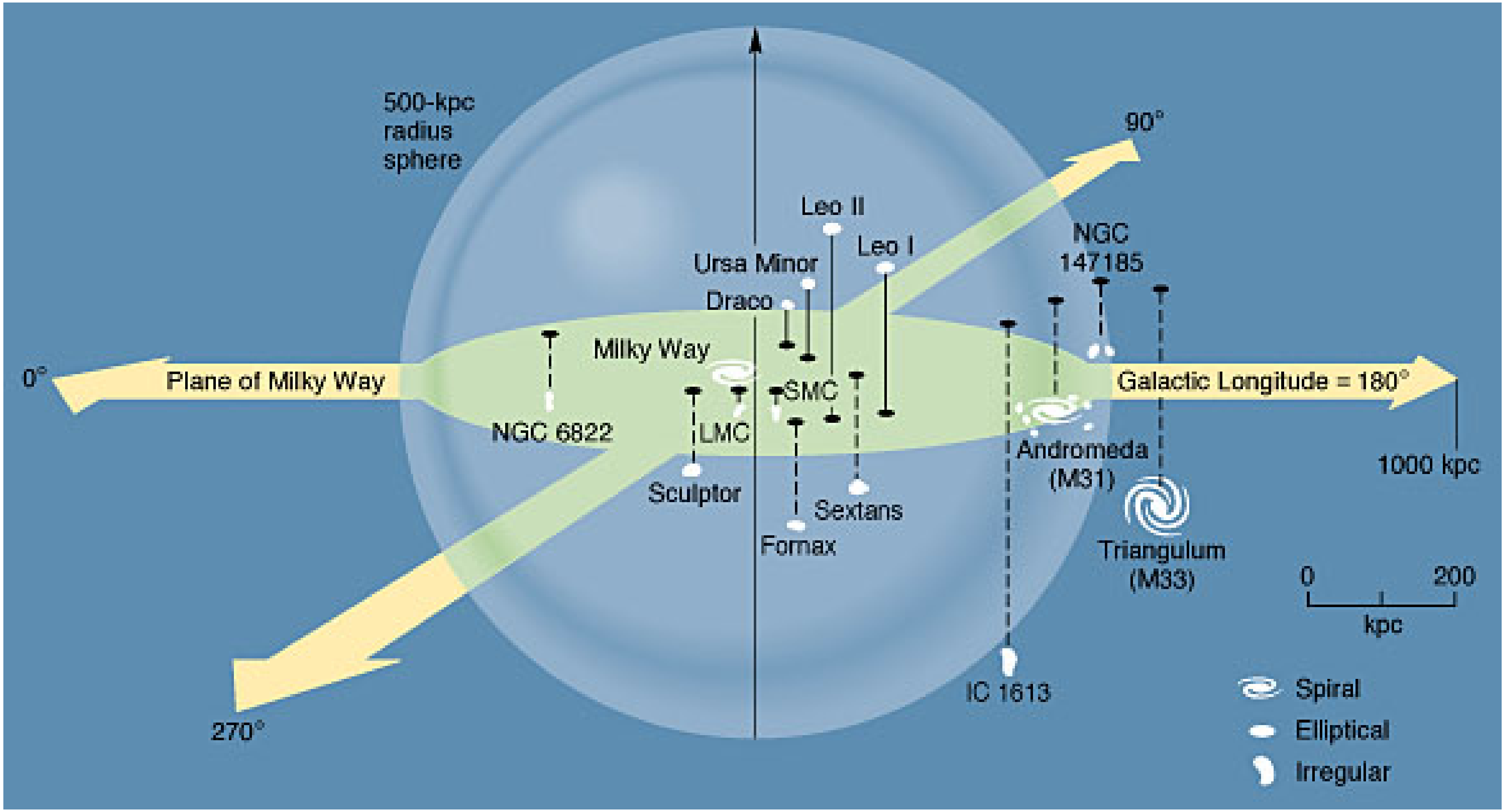
- Milky Way and M31 are the dominant galaxies in the group
- Many others are irregular or dwarf spheroidal
- Additional members are still being discovered



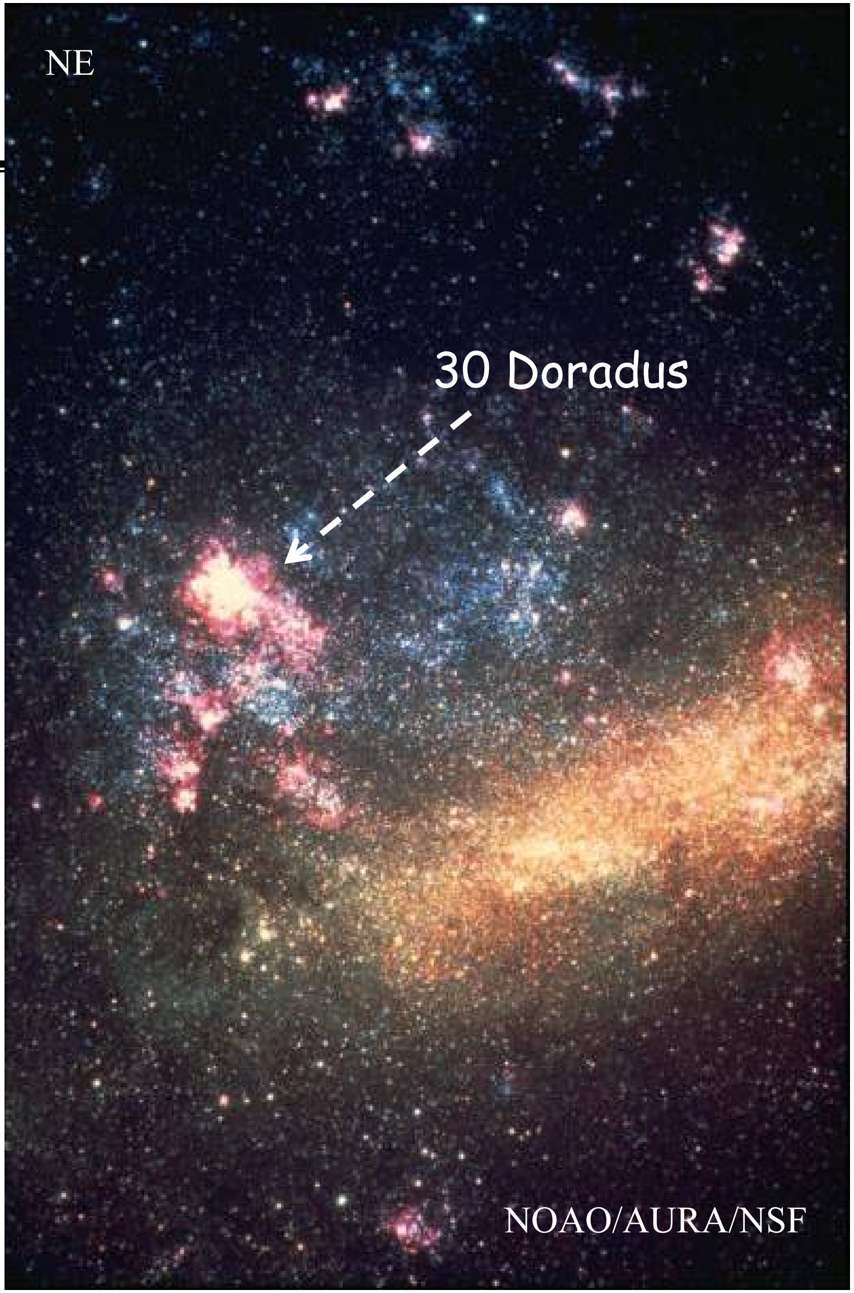
Local Group of Galaxies in 3D



One More Picture of the Local Group



LMC



Type: Irr/SB(s)m
Magnitude: 0.9
Size: 650 x 550 arcmin
~few kpc
Distance: ~50 kpc

Small Magellanic Cloud: SMC

Type: Im IV-V
Magnitude: 2.3
Size: 280 x 160 arcmin
<kpc
Distance: ~60 kpc

Andromeda Galaxy: M31

Type: SA(s)b I-II

(Hubble: ordinary spiral s-shaped with well defined arms)

Magnitude: 3.4

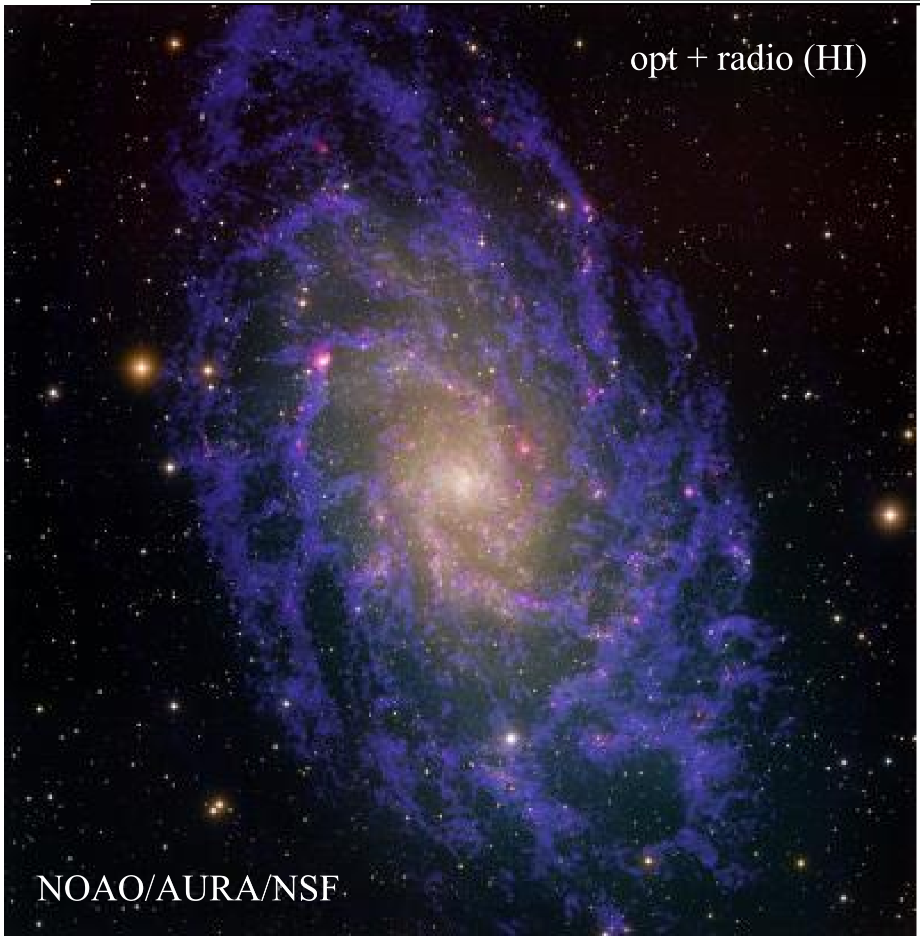
Size: 185.0 x 75.0 arcmin

>50 kpc

Distance: 725 kpc


NGC205
M32
NOAO/AURA/NSF

Triangulum Galaxy: M33



Type:	Mag:	Size:	Distance:
SA(s)cd II-III	5.7	67.0′x41.5′	795 kpc
(ordinary spiral s-shaped with loose arms)			>10 kpc

Summary: EGRET Observations

- LMC detection: CR density is similar to MW
- SMC non-detection: CR density is smaller than in the MW (otherwise it would be ~2.4×10^{-7} cm^{-2} s^{-1})
- CRs are galactic and not universal !

Source	F(>100 MeV), cm^{-2} s^{-1}
LMC	$(1.9\pm0.4)\times10^{-7}$
SMC	$<0.5\times10^{-7}$
M31	$<0.8\times10^{-7}$

Sreekumar et al.(1992-94)

- M31 non-detection: has to have smaller CR density than the MW (size M31>MW!)

L_{MW}(>100 MeV)~5.4×10^{39} erg/s (SMR00)
~3×10^{43} phot/s

F_{MW}(@M31 distance) ~ 4.4×10^{-7}cm^{-2} s^{-1}

Simplified diffuse emission model

- ✓ CR intensity is proportional to the rate of SN explosion ~R
- ✓ Assuming the same emissivity per H atom q_γ
- ✓ γ-ray luminosity is proportional to the total gas mass ~M
- ✓ Gamma-ray production: brems, IC, π^0 only π^0,brems
- ◆ [Source (injection) spectrum same as in MW]
- ✗ Interstellar radiation field (IC, $e^\pm$ energy losses)
- ✗ Nuclear & particle production cross sections
- ✗ Energy losses: ionization, Coulomb, brems, IC, synch
- ✗ Transport equations for all CR species
- ✗ Fix propagation parameters

Some Math (Pavlidou & Fields 2001)

Transport equation for CR number density (steady-state leaky-box):

$$\frac{\partial N_i(T,t)}{\partial t} = Q_i(T,t) + \frac{\partial}{\partial T}[b_i(T)N_i(T,t)] - \frac{1}{\tau_{\rm esc}} N_i(T,t)$$

Trivial solution:

$$0 = Q_p(T) - \frac{1}{\tau_{\rm esc}} N_p(T)$$

In terms of CR flux:

$$\phi_p(T) = l_{\rm esc}\, Q_p(T)$$

$$l_{\rm esc} = \tau_{\rm esc}\, v \qquad l_{esc}(G) \sim l_{esc}(MW)$$

Assuming CR injection rate proportional to SN rate: $Q_p^G \propto \mathcal{R}_G$

CR flux in a galaxy G:

$$\frac{\phi_p^G}{\phi_p^{\rm MW}} = \frac{\mathcal{R}_G}{\mathcal{R}_{\rm MW}} = f_G$$

Some Math (cont'd)

γ-ray flux from a galaxy:

$$F_\gamma^G = \frac{1}{4\pi d^2}\frac{M_{\rm gas}}{m_p} q_\gamma^G$$

$$q_\gamma^G(>100~{\rm MeV}) = 2.36\times 10^{-25} f_G~{\rm photons~s^{-1}~(H~atom)^{-1}}$$

Emissivity calcs q(>100 MeV): pp→ π^0 x1.55 (bremss) x1.5 (A>1 nuclei)

Combined:

$$F_\gamma^G(>100~{\rm MeV}) = 2.34\times 10^{-8} f_G \frac{M_{\rm gas}}{10^8~M_\odot} \times \left(\frac{d}{100~{\rm kpc}}\right)^{-2} {\rm photons~cm^{-2}~s^{-1}}$$

Properties of the LG galaxies & γ-ray flux

Observed Properties of Selected Local Group Galaxies

$$\Sigma = \frac{M_{gas}}{d^2}$$

Galaxy		SN Rate (century^{-1})	Adopted f	Σ HI ($\times 10^4\ M_\odot$ kpc^{-2})	$M_\odot$	Σ H_2 ($\times 10^4\ M_\odot$ kpc^{-2})	$M_\odot$	Σ total ($\times 10^4\ M_\odot$ kpc^{-2})	$M_\odot$
LMC	50 kpc	0.1,[a] 0.23,[b] 0.49[c]	0.14	22 ± 6[d,e,f,g]	5.5×10^8	4.63[g]	1.2×10^8	26.6	6.7×10^8
SMC	60 kpc	0.065,[b] 0.12[c]	0.04	17 ± 4[d,h]	6.1×10^8	0.76[g]	0.3×10^8	17.8	6.4×10^8
M31	725kpc	0.9,[i] 1.21,[c] 1.25[j]	0.45	0.9 ± 0.2[d,k]	4.7×10^9	0.06[l]	0.3×10^9	0.92	5.0×10^9
M33	795kpc	0.28,[m] 0.35,[i] 0.68[c]	0.17	0.26 ± 0.05[d]	1.6×10^9	0.004[n]	0.3×10^8	0.264	1.6×10^9
NGC 6822		0.04[o]	0.02	0.05 ± 0.02[d]		0.006[p]		0.056	
IC 10		0.082–0.11[q]	0.04	0.016 ± 0.003[r]		$\gtrsim 10^{-5}$[s]		0.016	
MW		~2.5		HI ~ H_2					$(2-6)\times10^9$

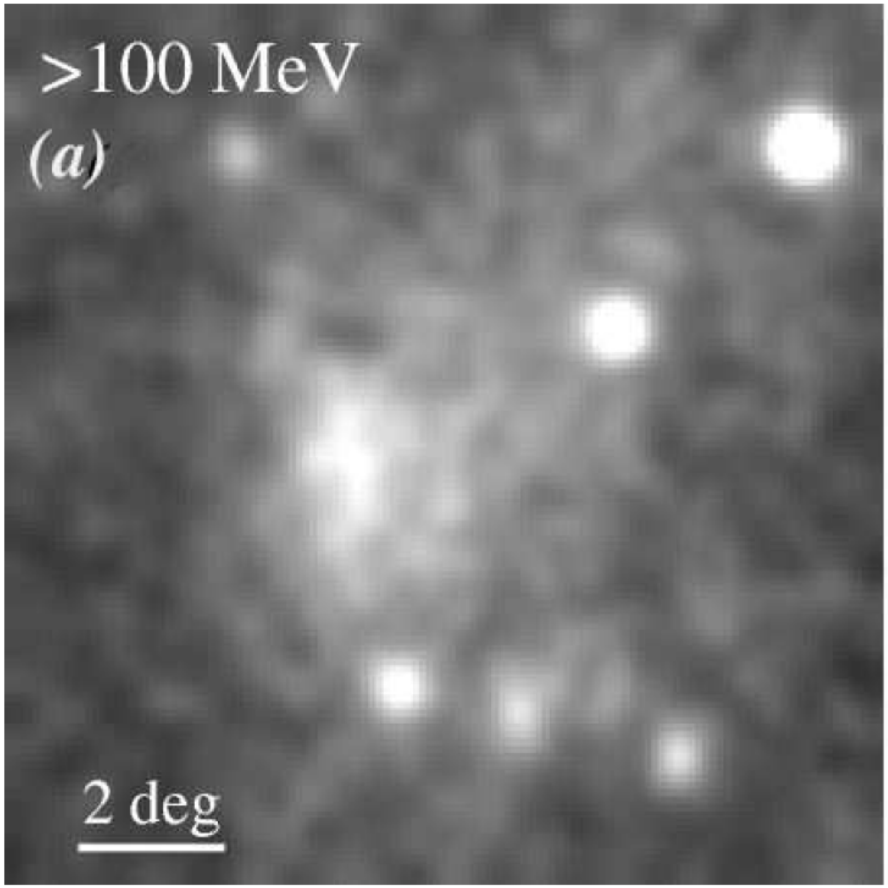
Predicted Gamma-Ray Flux and *GLAST* Requirements for Selected Local Group Galaxies

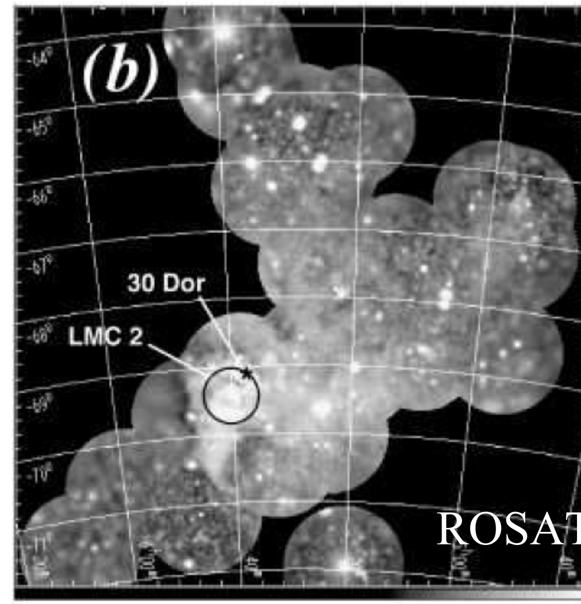
Galaxy	Flux > 100 MeV: Prediction (photons cm^{-2} s^{-1})	Flux > 100 MeV: EGRET Value/Limit (photons cm^{-2} s^{-1})	*GLAST* Significance: 2 yr (σ)	*GLAST* Significance: 10 yr (σ)	*GLAST* On-Target 5 σ Exposure Time (yr)
LMC	11×10^{-8}	$(14.4 \pm 4.7) \times 10^{-8}$	42	93	4.6×10^{-3}
SMC	1.7×10^{-8}	$< 4 \times 10^{-8}$	19	43	2.1×10^{-2}
M31	1.0×10^{-8}	$< 1.6 \times 10^{-8}$	13	31	4.1×10^{-2}
M33	0.11×10^{-8}	...	1.9	4.1	2.31
NGC 6822	2.6×10^{-11}	...	0.04	0.09	$\gg 10$
IC 10	2.1×10^{-11}	...	0.02	0.05	$\gg 10$

- ✓ Order of magnitude estimates show that LMC, SMC, M31, M33 will be detectable by GLAST, but…

- GLAST will resolve these galaxies so we need more detailed modeling

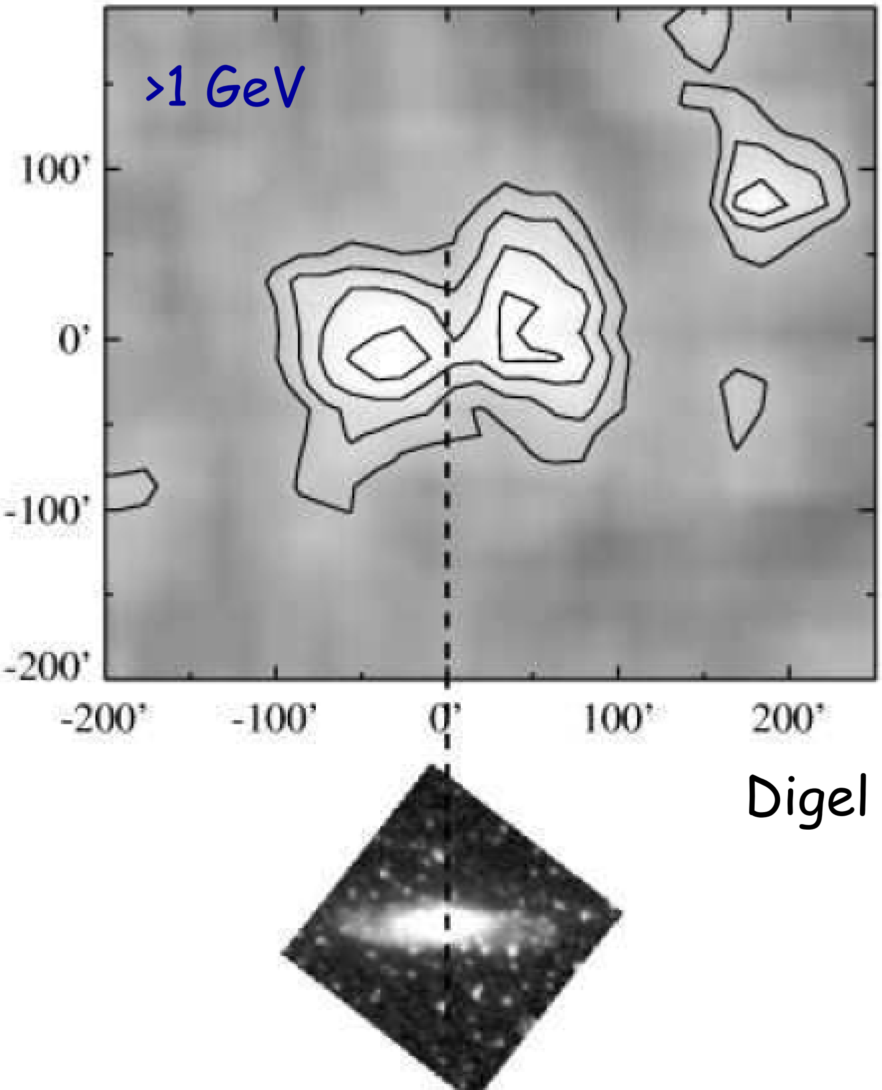
LMC Observations by GLAST (simulation)

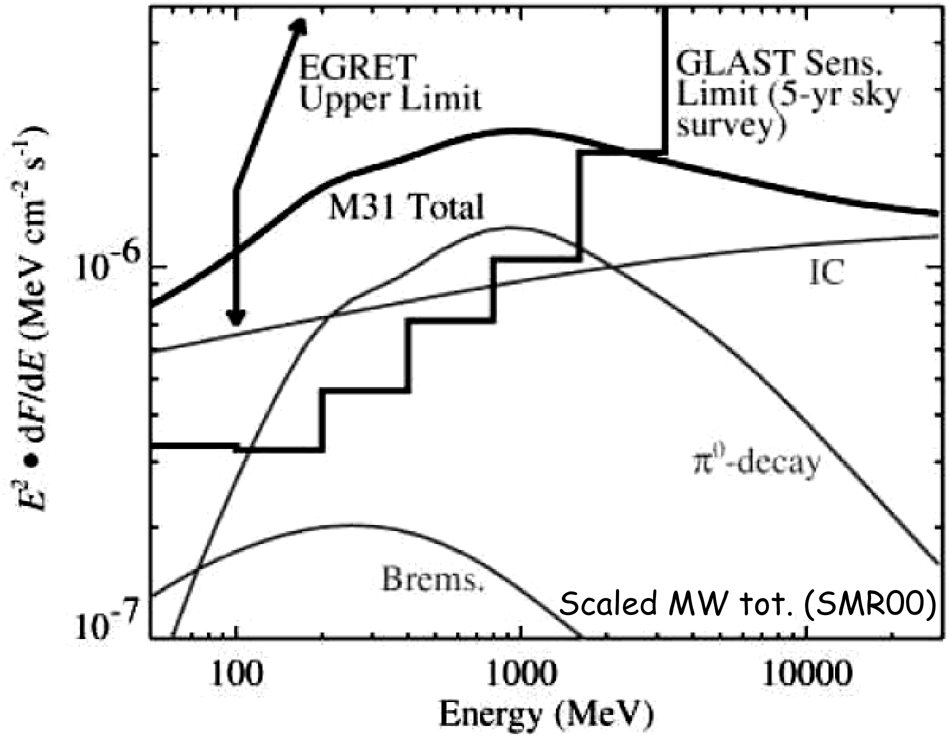




Digel et al. (2000)

M31 Observations by GLAST (simulation)





Digel et al. (2000)

More Sophisticated Modeling of diffuse emission

- SNR rate and distribution
- Gas distribution (at least, surface column density)
- Magnetic field
- Interstellar radiation field
- Estimates of pulsar contribution (using MW observations)

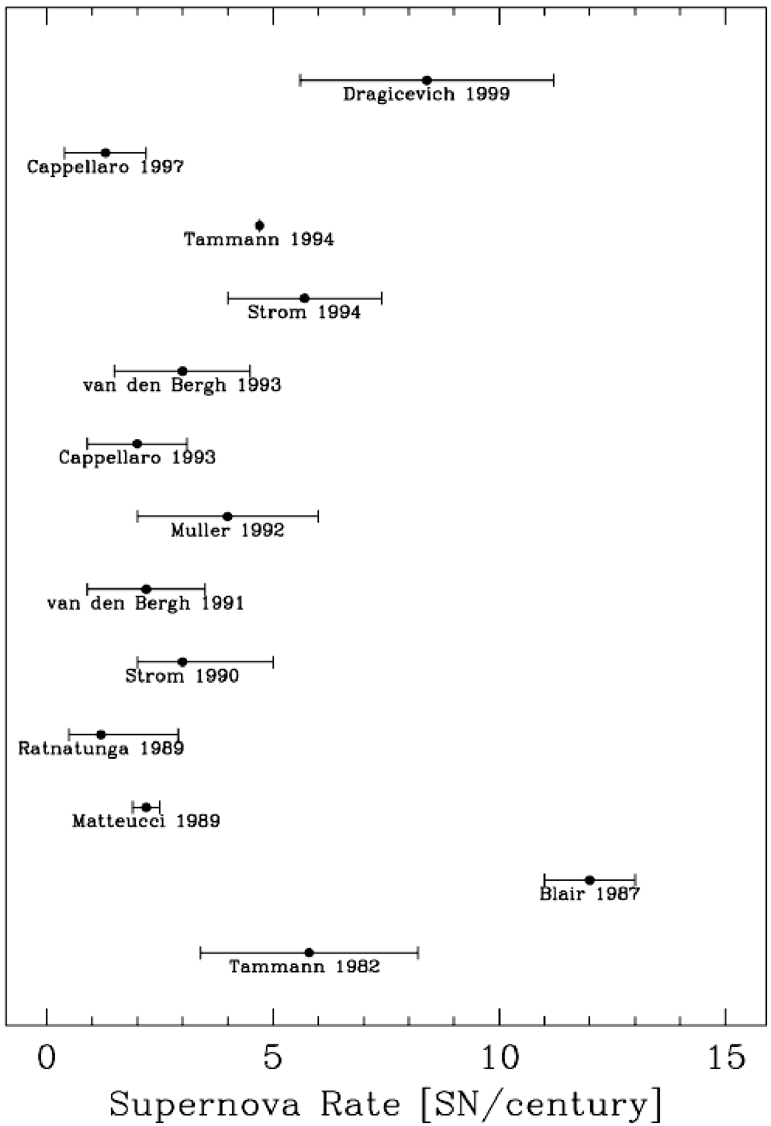
No new calculations yet!

MW SN Rate

SN rate determination:

- Massive star formation rate (1.2 +1.7-0.7)
- Chemical evolution (1.9, 2.5)
- From the historical records (2-9)
- Extragalactic SN discoveries (2-5)

MW average ~2.5±? per century



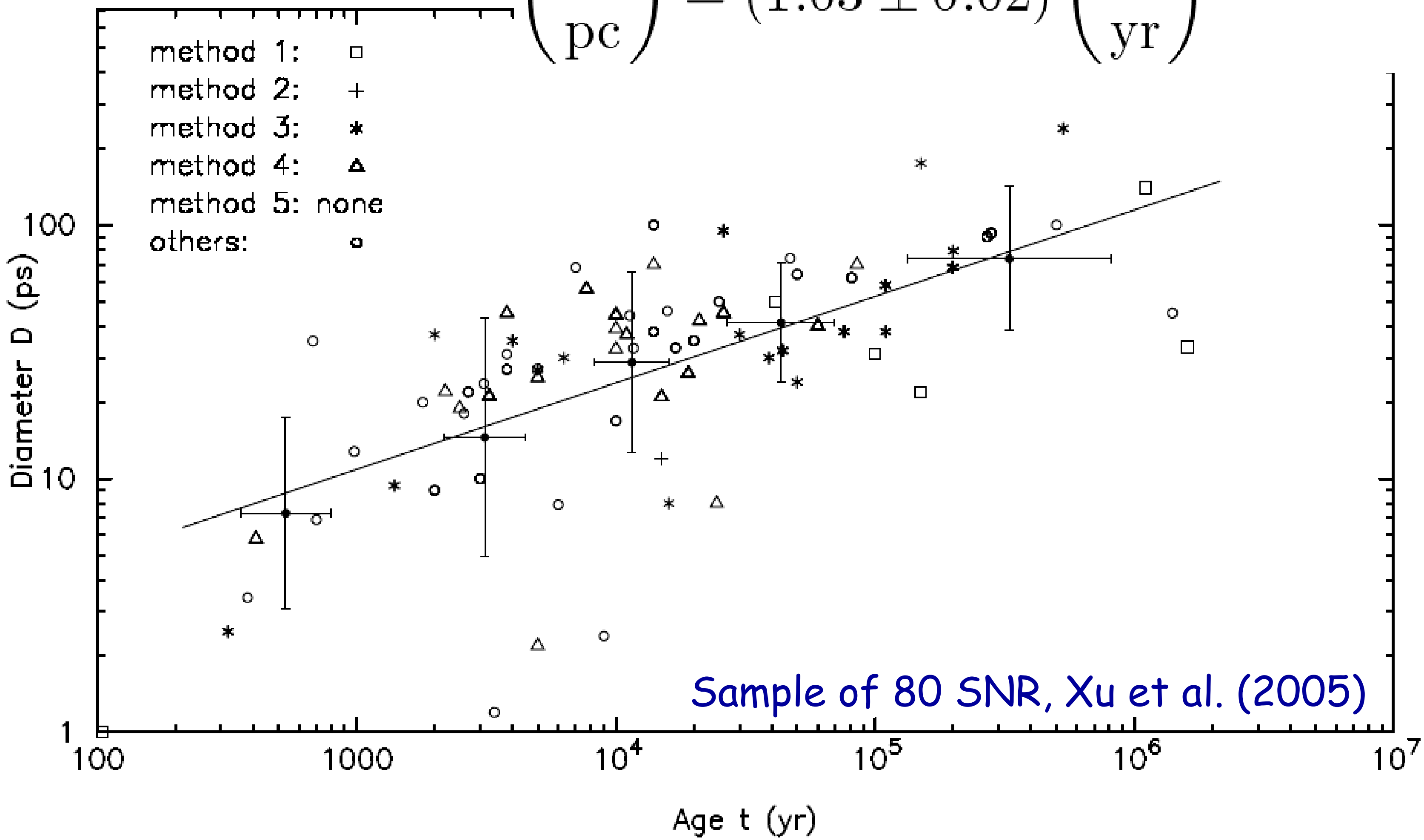
Example: SN age estimates

- Association with a pulsar → $t=P/(2dP/dt)$
- Using total SN explosion energy and energy loss → $t=E_{tot}/(dE/dt)$
- Using SNR diameter and expanding velocity → $t=DC/2v_s$
  - C=1 freely expanding SNR
  - C=2/5 adiabatic expansion (Sedov phase)
  - C=2/7 radiative expansion
- Using radius and temperature (X-rays) →
  - $t=380\ R_{pc}\ (kT,keV)^{-1/2}$ yr
- Using synchrotron break frequency →
  - $t=40000\ B^{-3/2}\ \nu_b^{-1/2}$ yr

Distance determination (SN mag., SNR kinematics, HI abs. etc.)

Example: D vs. t

$$\left(\frac{D}{\mathrm{pc}}\right) = (1.03 \pm 0.02)\left(\frac{t}{\mathrm{yr}}\right)^{0.34\pm0.02}$$



Sample of 80 SNR, Xu et al. (2005)

Distribution(s) of Extragalactic SNR

"Blue" & FIR luminosities of a galaxy & Hα

1 SNu = N/(10^{10} $L_{B\bullet}$) per century

MW (Sb) ~2.0x10^{10} $L_{B\bullet}$x1.21 ~2.4 cy^{-1}

Table 4. SN rate(in SNu) from the combined search sample. Cappellaro et al. (1999)

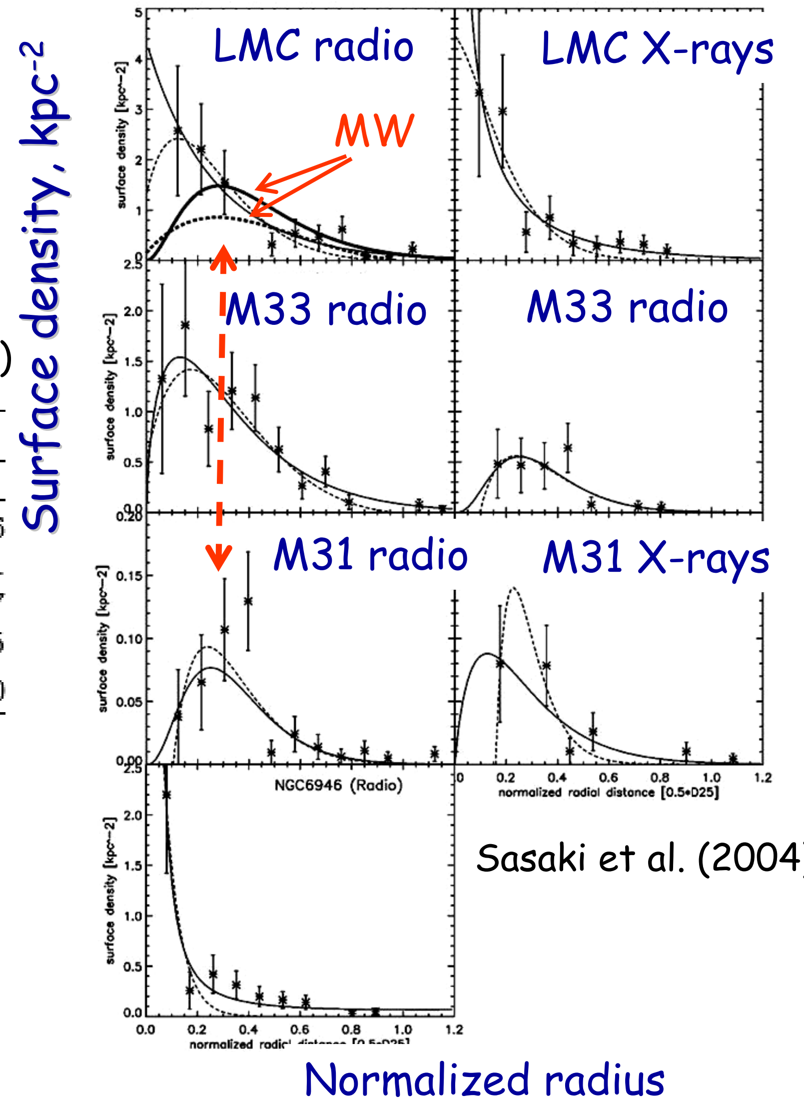
galaxy type	N. SNe* Ia	Ib/c	II	rate [SNu] Ia	Ib/c	II	All
E-S0	22.0			0.18 ± 0.06	< 0.01	< 0.02	0.18 ± 0.06
S0a-Sb	18.5	5.5	16.0	0.18 ± 0.07	0.11 ± 0.06	0.42 ± 0.19	0.72 ± 0.21
Sbc-Sd	22.4	7.1	31.5	0.21 ± 0.08	0.14 ± 0.07	0.86 ± 0.35	1.21 ± 0.37
Others#	6.8	2.2	5.0	0.40 ± 0.16	0.22 ± 0.16	0.65 ± 0.39	1.26 ± 0.45
All	69.6	14.9	52.5	0.20 ± 0.06	0.08 ± 0.04	0.40 ± 0.19	0.68 ± 0.20

Tammann et al. (1994)

SN Frequencies in Local Group Galaxies

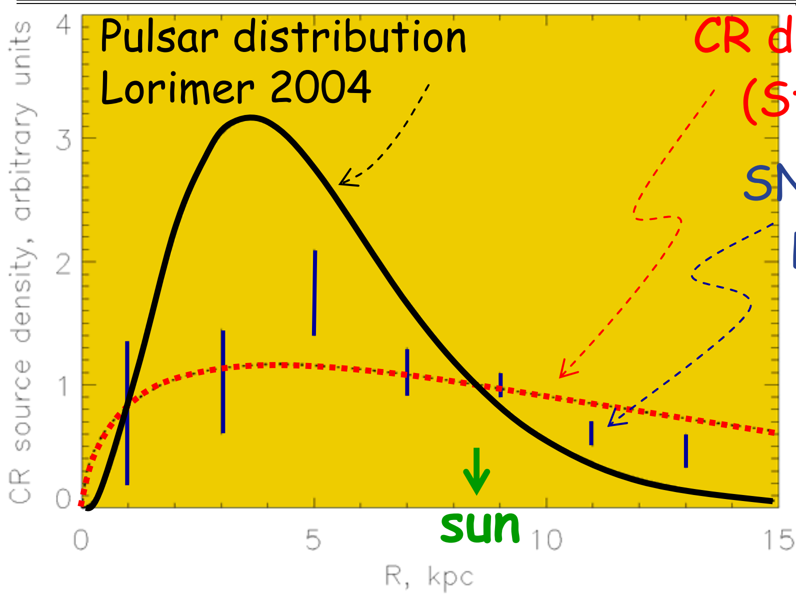
Parameter	Galaxy and Type LMC Sm	SMC Im	M31 Sb	M33 Sc
n (Ia)[a]	0.04	0.01	0.38	0.06
n (II + Ib)[a]	0.45	0.11	0.83	0.62
τ (yr)	204	833	83	147

[a] Number per 100 yr.



Sasaki et al. (2004)

Distribution of CR Sources & Gradient in the CO/H_2



X_{CO}=N(H_2)/W_{CO}:

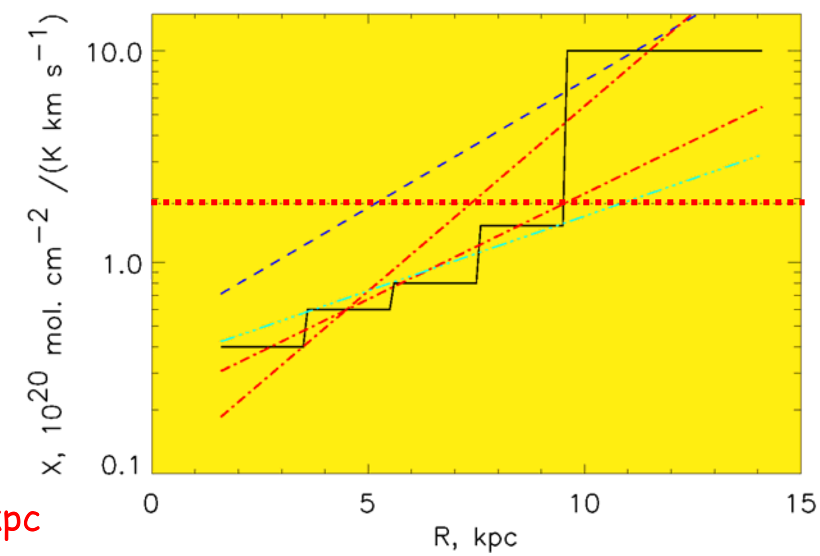
Histo –This work, Strong et al.'04

----- -Sodroski et al.'95,'97

1.9×10^{20} -Strong & Mattox'96

$\sim Z^{-1}$ -Boselli et al.'02

$\sim Z^{-2.5}$ -Israel'97,'00, [O/H]=0.04,0.07 dex/kpc



ATCA Statistics of Extragalactic SNRs

Synch. luminosity $L_\nu \sim \nu^\alpha$

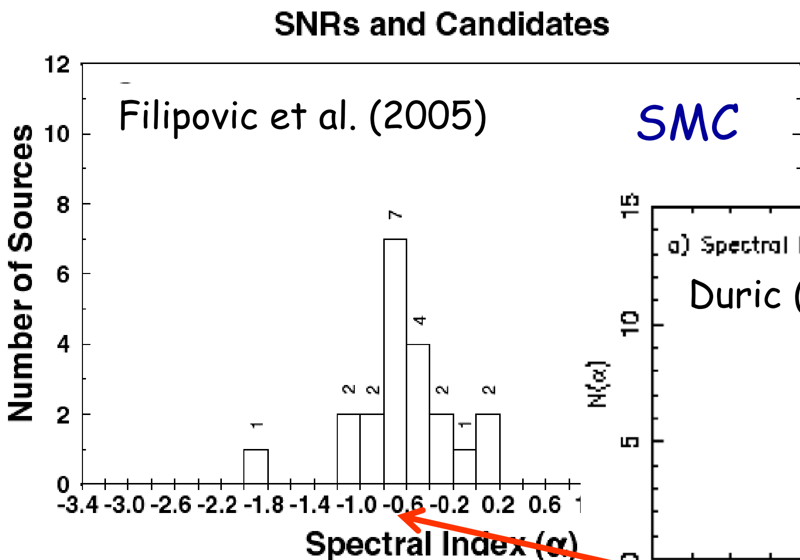
Electron spectrum $N_e \sim p^\gamma$

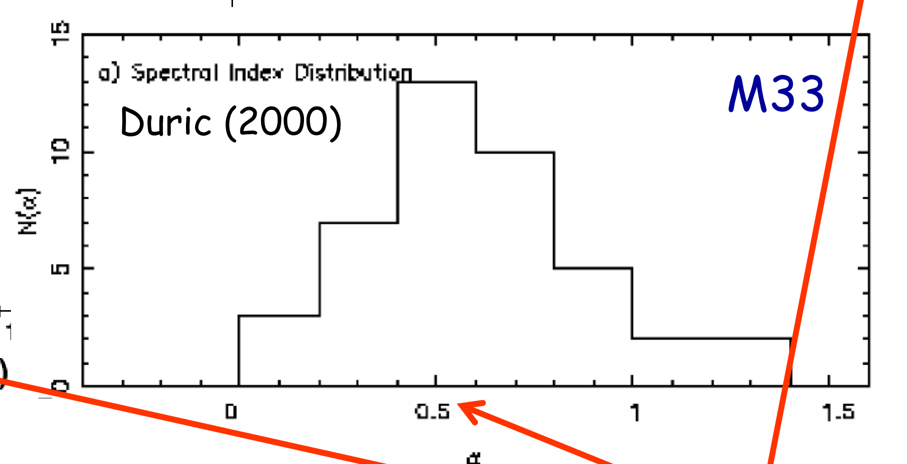
Index relationship $\alpha=(\gamma+1)/2$

Table 6. Spectral index distribution by source type. FHW98 in Column 5 stands for Filipović et al. (1998a).

SMC

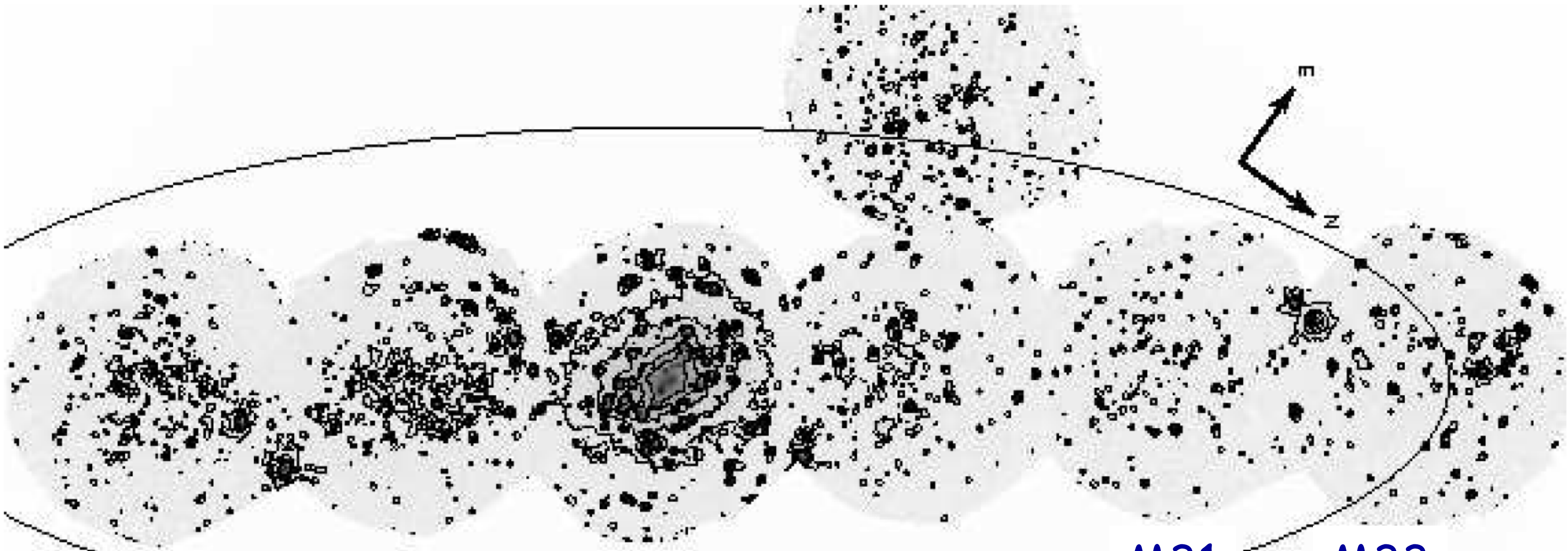
Source type	Number of sources	Mean α	s.d.	FHW98 ATCA No. /α/s.d.
Known SNRs	16	−0.58	0.33	–
Candidate SNRs	5	−0.77	0.69	–
All SNRs	21	−0.63	0.43	12/−0.22/0.25
Background	534	−0.9[illegible]	0.61	63/−0.45/0.48
Total SMC	621	−0.87	0.69	164/−0.73/0.61





Indicates same SNR physics as in the MW (electron index γ~-2)

SNRs in M31 (XMM-Newton)



Pietsch (2005)

SNR(M31) =44

SNR(M33) =44

	M31		M33	
Source type	ident.	class.	ident.	class.
fg Star	6	90	5	30
AGN	1	36		12
Gal	1		1	1
GalCl	1	1		
SSS		18		5
SNR	21	23	21+2	23-2
GlC	27	10		
XRB	7	9	2	
hard		567		267

Starburst regions in LMC

8.6 GHz map HII (greyscale)

+CO (red)
+stellar
complexes

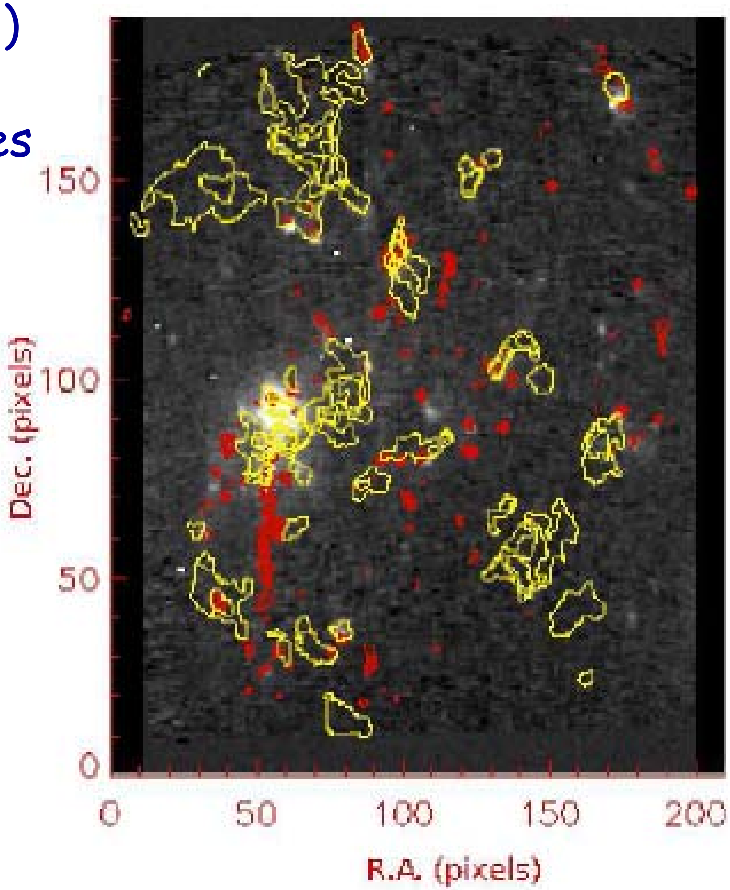


Fig. 3. Maps of the LMC at 8.6 GHz (grey-scale) and in the CO(1→0) line (red contours), with the stellar complexes superimposed with yellows lines.

Complex Type	F_{60} (Jy)	8.6 (GHz)	No. of Complexes
starburst	$F_{60} > 5.4$	yes	13
starburst candidate	$F_{60} \gtrsim 5.4$	yes	5
active complex candidate	$F_{60} \lesssim 5.4$	no	2
active complex	$F_{60} < 5.4$	no	36

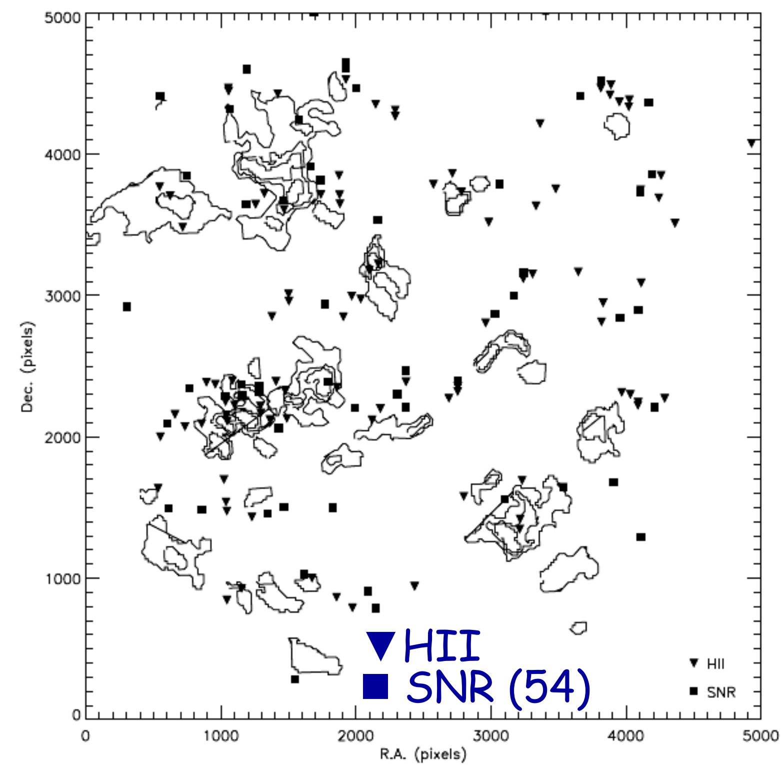
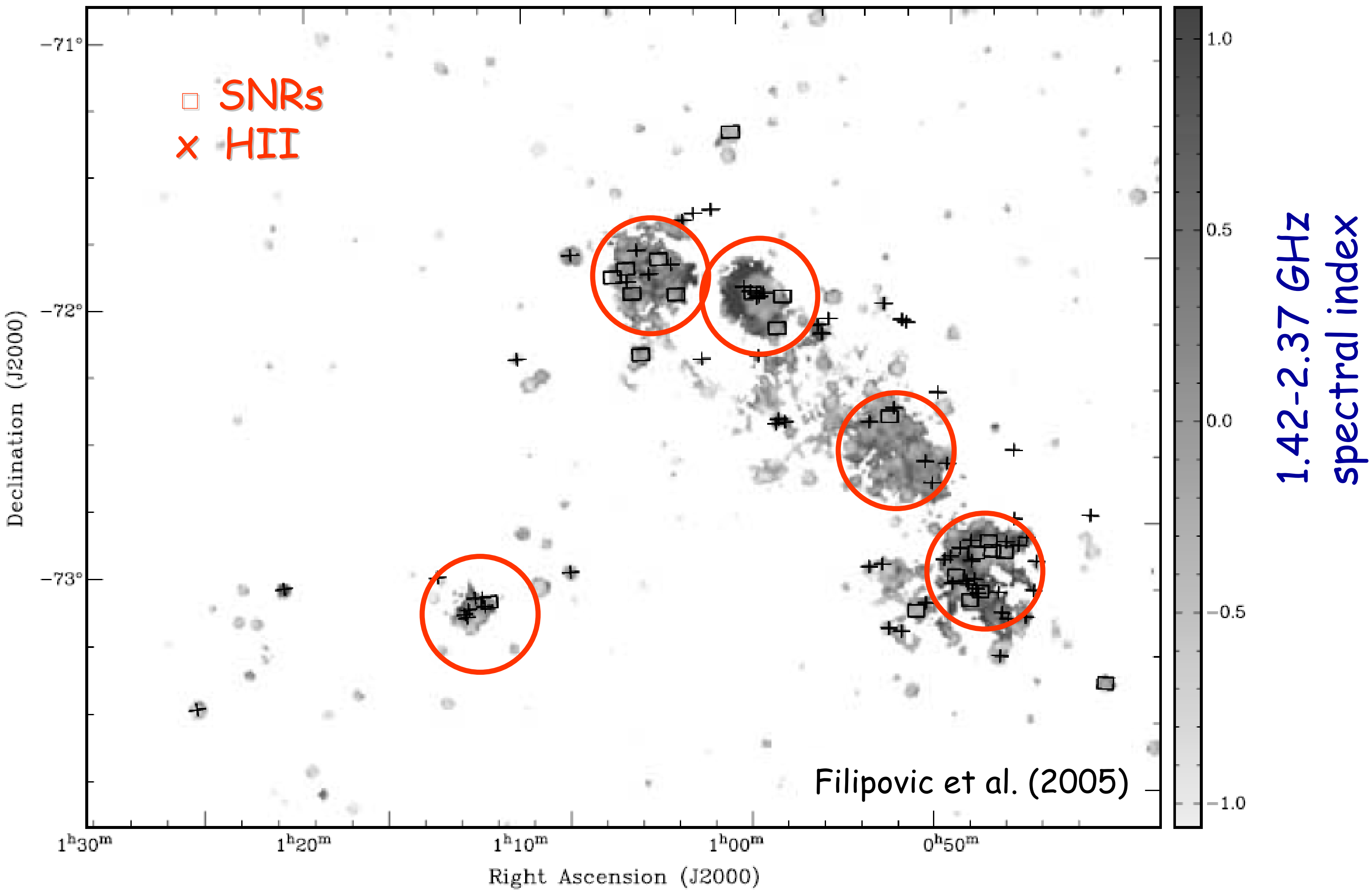
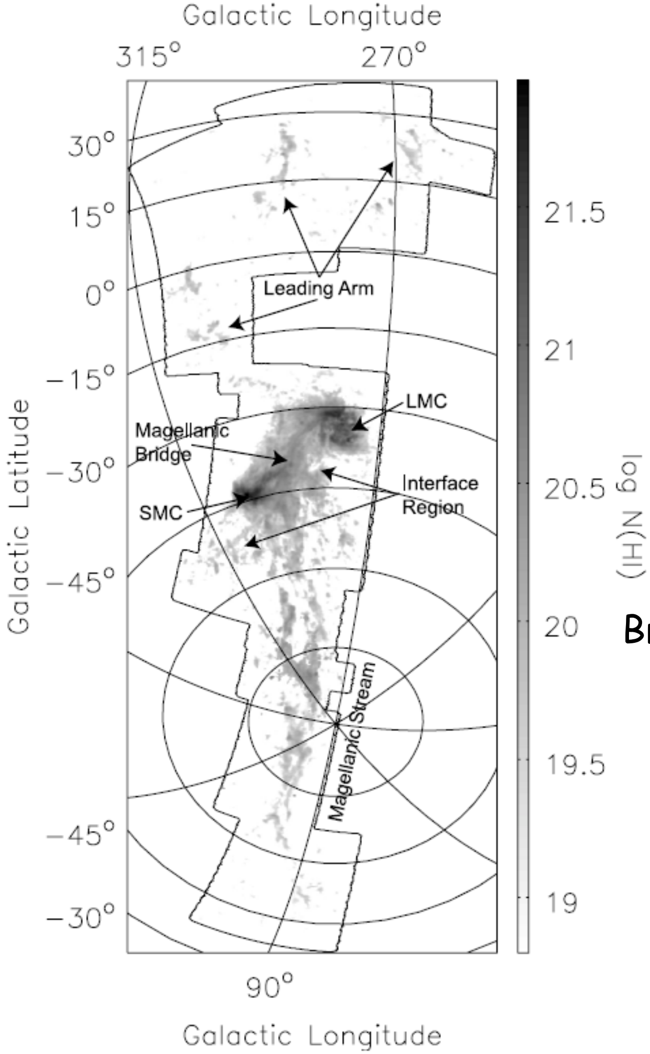


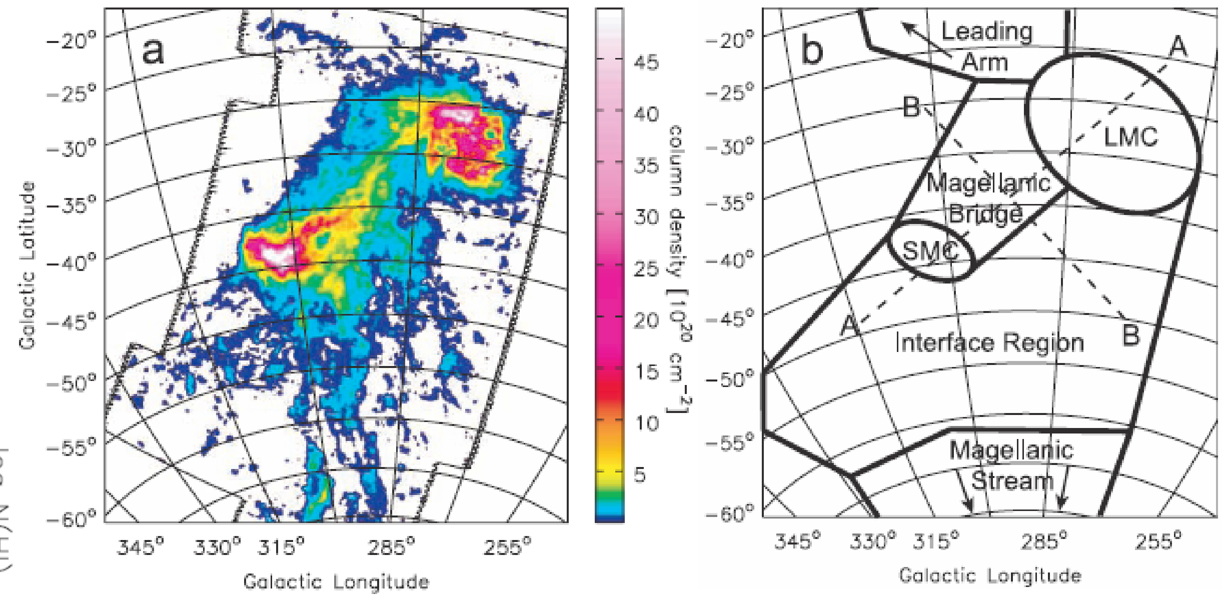
Fig. 4. The HII regions (triangles) and SNRs (squares), plotted over the stellar complexes as defined here.

SMC: SNRs and HII Regions with radio index



Parkes HI survey: LMC & SMC



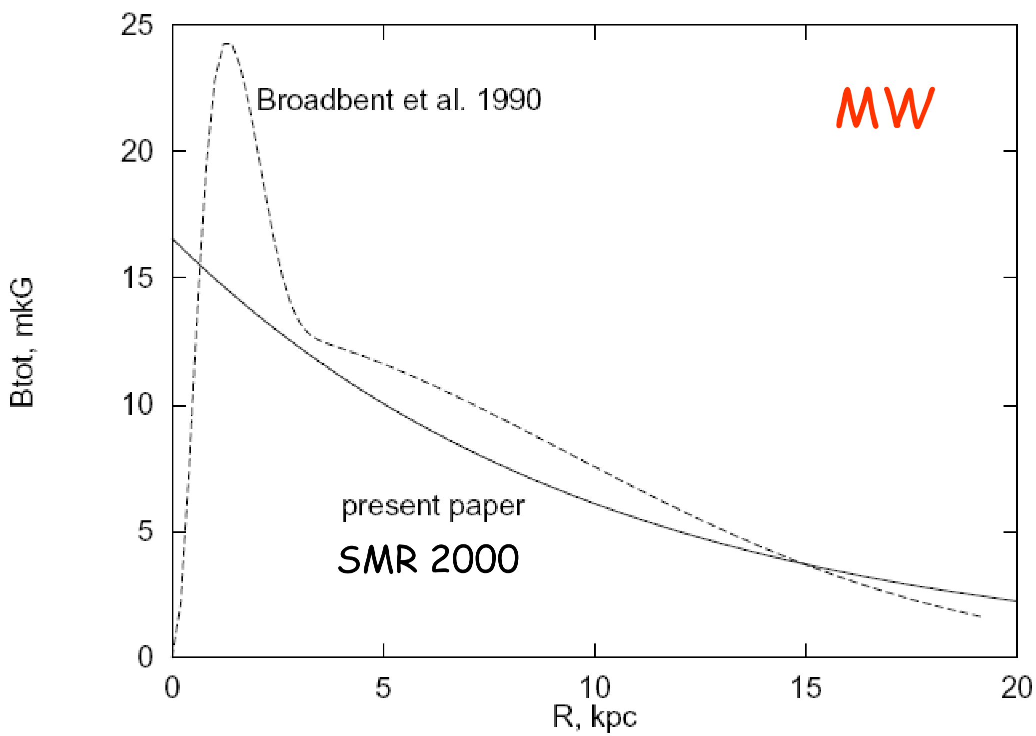


Brüns et al. (2005)

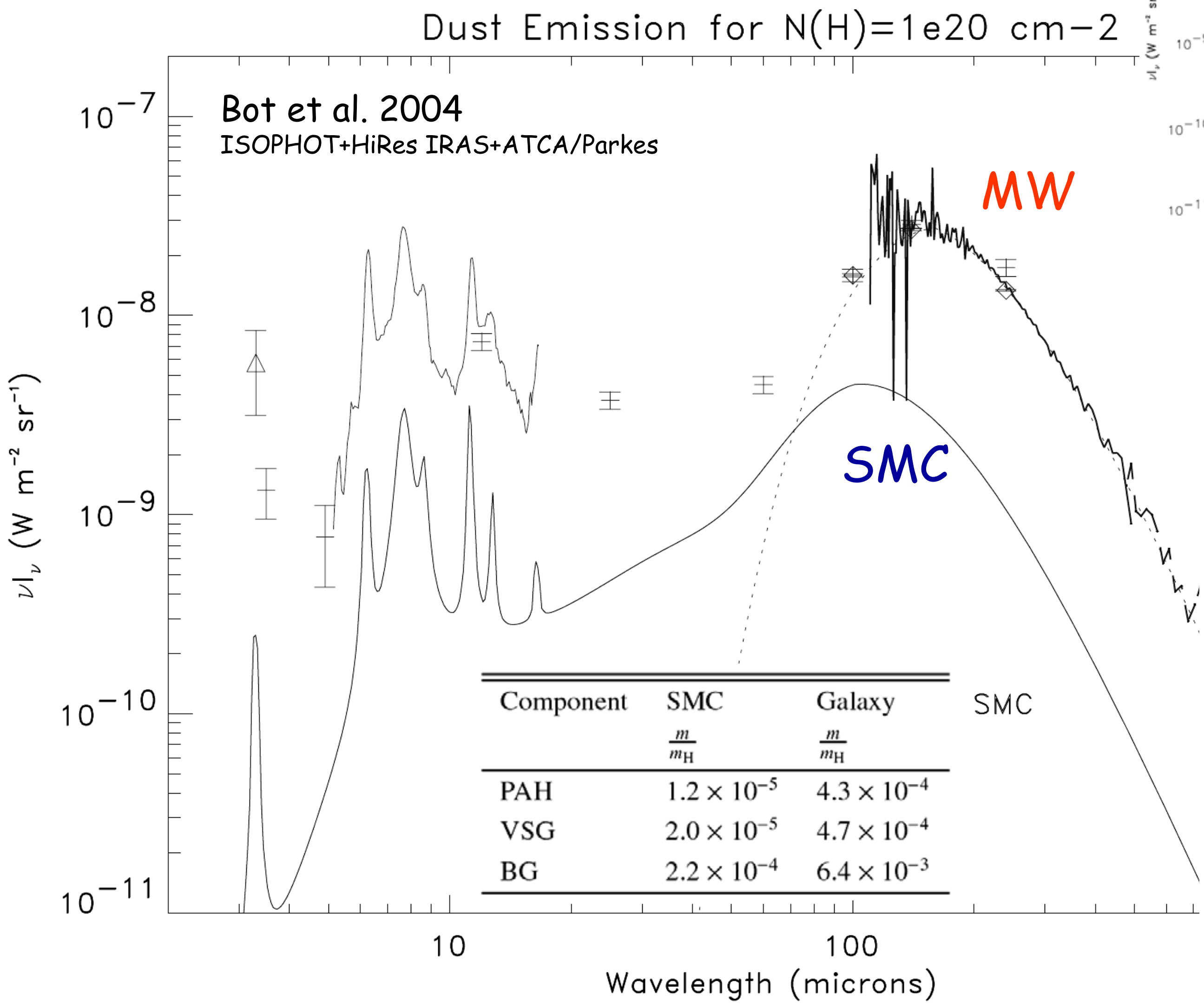
	HI (x10^8 $M_\odot$)
LMC	(4.41±0.09)x[d/50kpc]^2
SMC	(4.02±0.08)x[d/60kpc]^2
Bridge	1.84x[d/55kpc]^2
Interface	1.49x[d/55kpc]^2

Magnetic Field

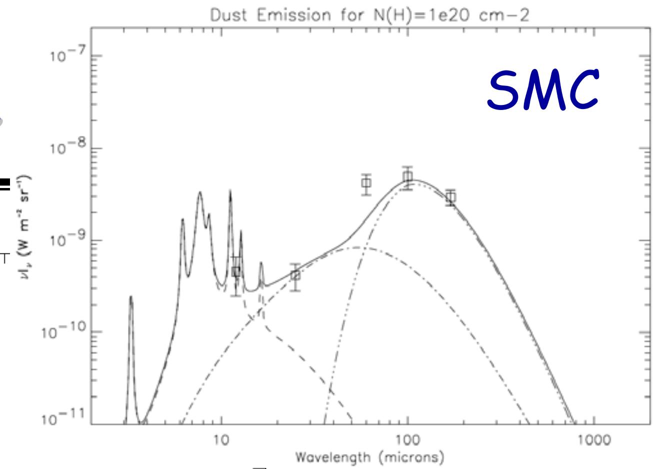
	B-reg	B-rand	B-tot	z-scale, kpc		
LMC	1.1 μG	4.1 μG	4.6 μG			Gaensler et al. (2005)
M31	~5 μG	~5 μG	~7.1 μG	>1 kpc	(6-14kpc)	Fletcher et al. (2004)
(axisymmetric)						

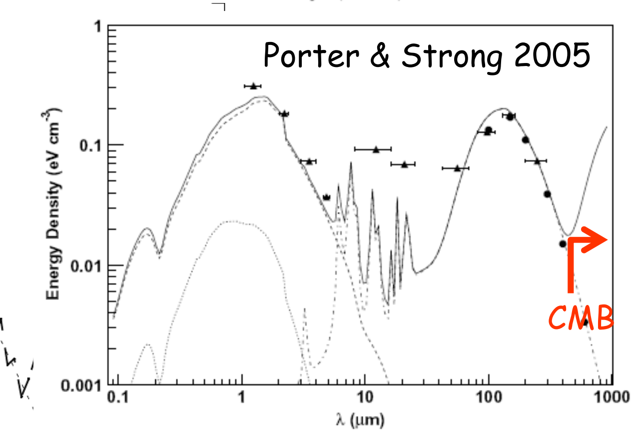


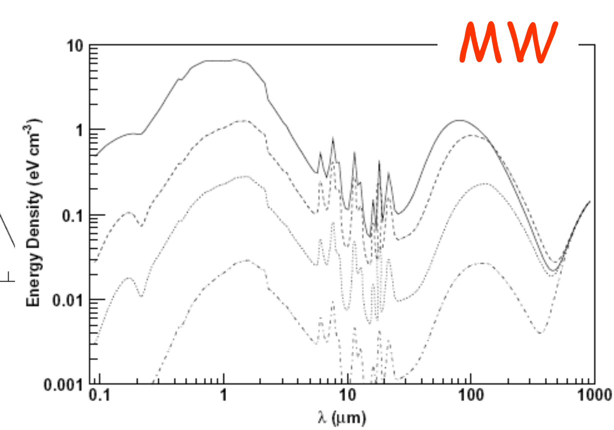
Interstellar Radiation Field: SMC



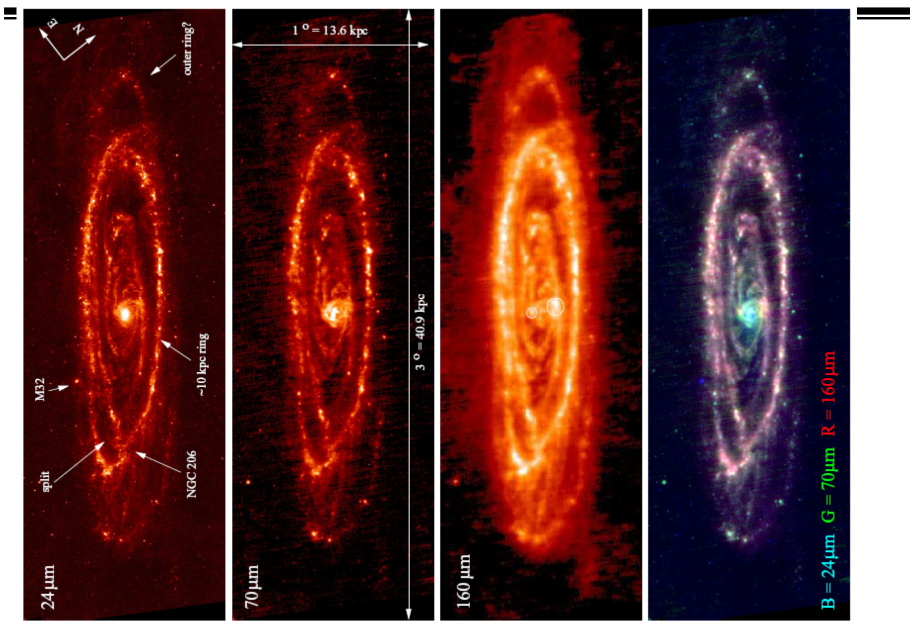
Component	SMC $\frac{m}{m_H}$	Galaxy $\frac{m}{m_H}$
PAH	1.2×10^{-5}	4.3×10^{-4}
VSG	2.0×10^{-5}	4.7×10^{-4}
BG	2.2×10^{-4}	6.4×10^{-3}



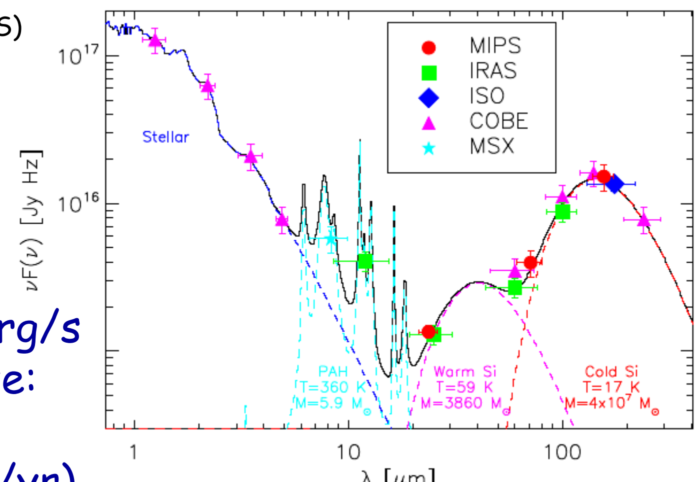


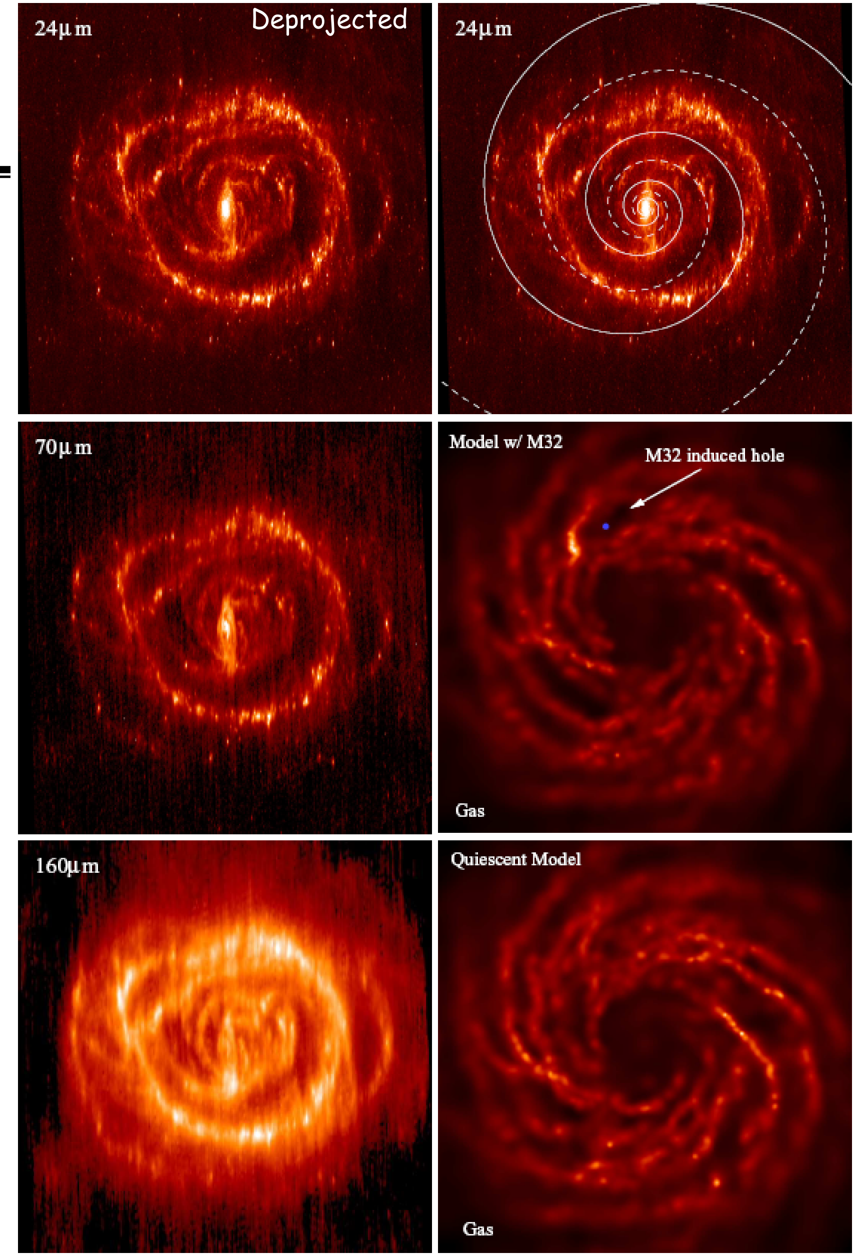


Interstellar Radiation Field: M31



Gordon et al. 2006 (MIPS)





L_{IR}~1.7×10^{43} erg/s
Star form. rate:
~0.75 M_*/yr
(cf. MW ~3M_*/yr)

Pulsar Contribution: LMC

$$L_\gamma \approx 3.6\times 10^{31} f^3 P^{-4} B_{12}^2 \text{ erg s}^{-1},$$

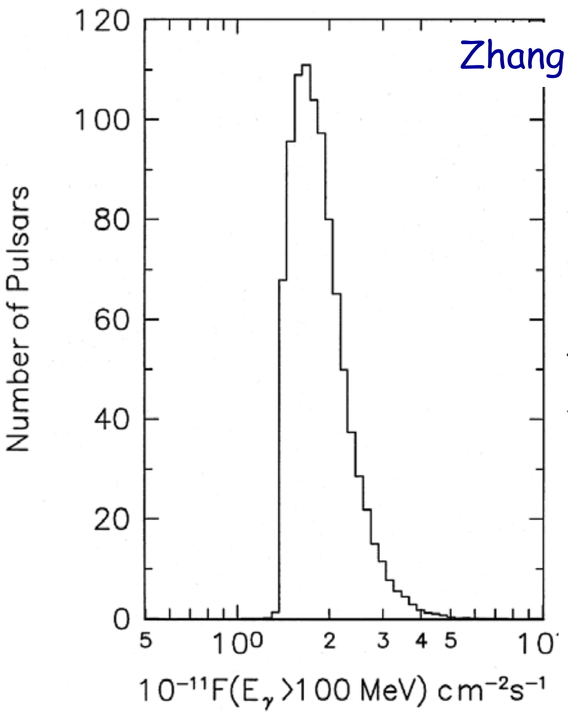
where $f \approx 5.5 P^{26/21} B^{-4/7}$

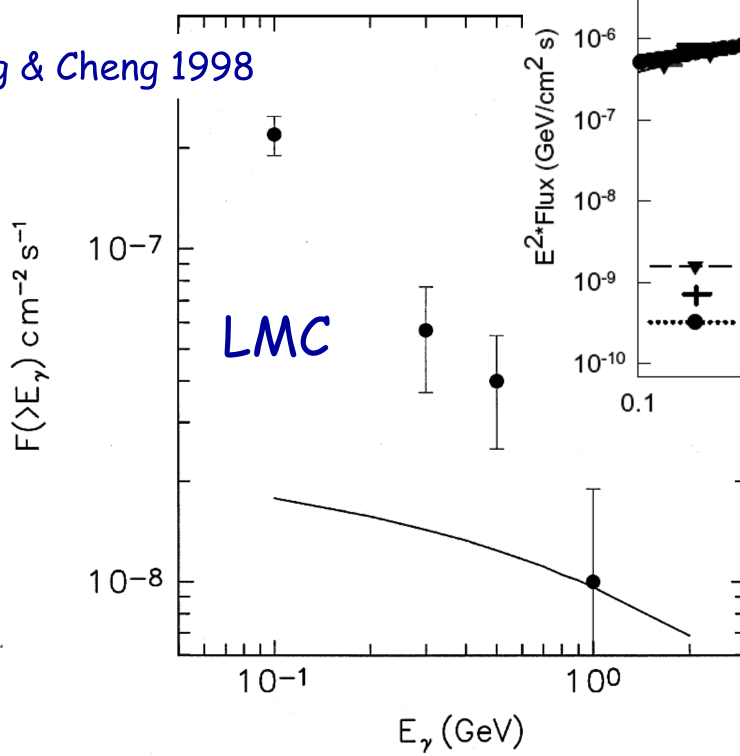
Pulsar statistics: using MW pulsar observations

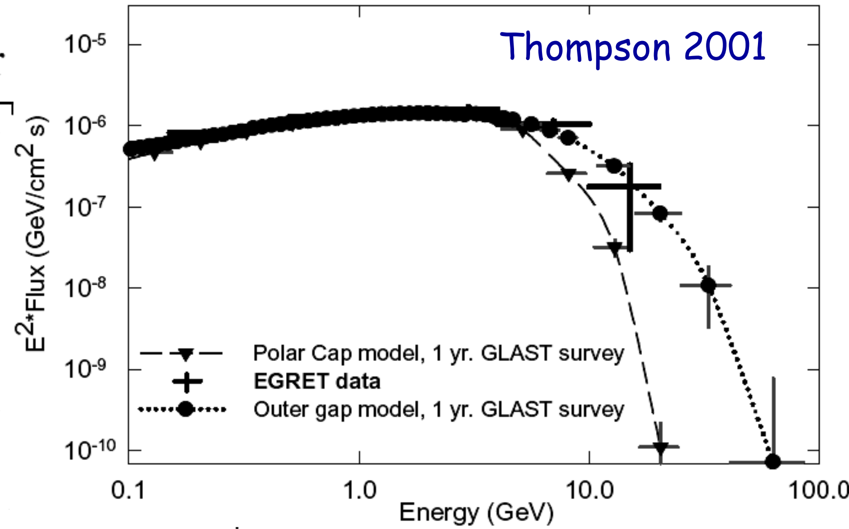
$$F(E_\gamma \geq 100\text{ MeV}) \sim 1.7\times 10^{-8} \dot{N}_{500} d_{50}^{-2} \text{ photon cm}^{-2}\text{ s}^{-1},$$

where $\dot{N}_{500}$ is the birth rate in units of one per 500 yr

Zhang & Cheng 1998







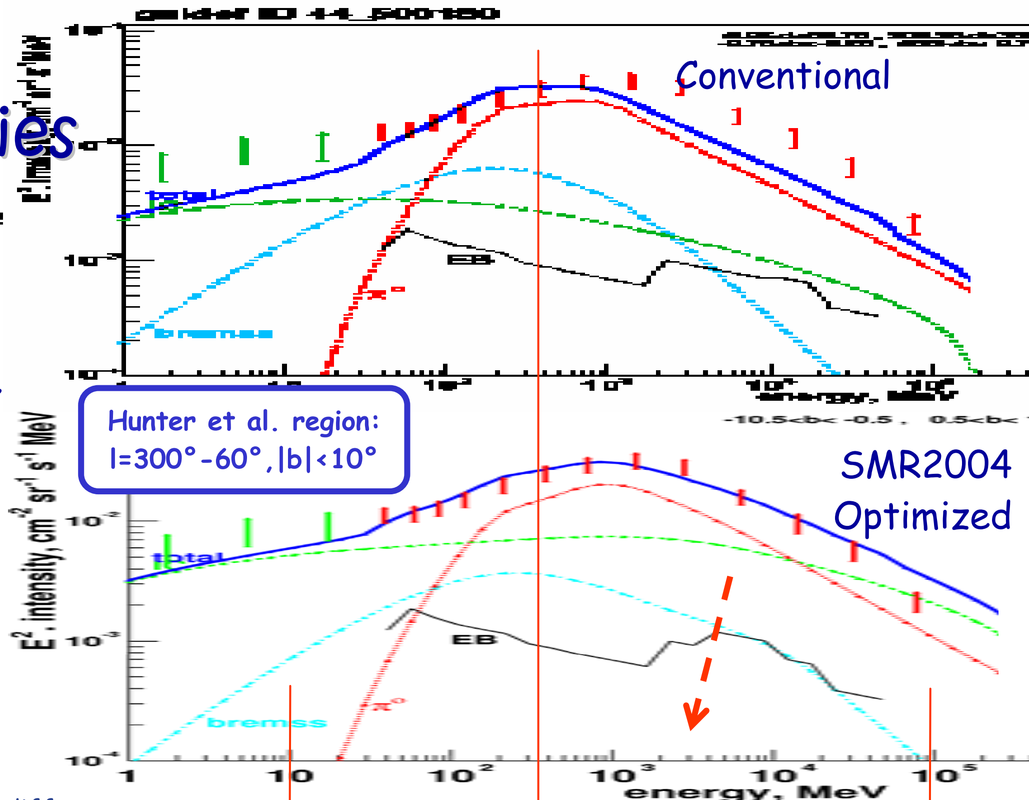
EB frm Normal Galaxies

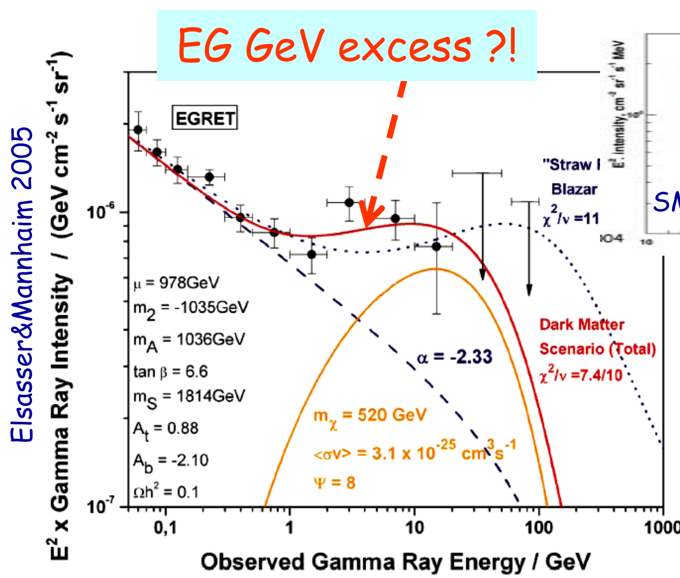
$$L_\gamma(z,E) = \frac{\psi(z)}{\psi_{MW}}\frac{\mu(z)}{\mu(0)} L_{\gamma,\,MW}(E)$$

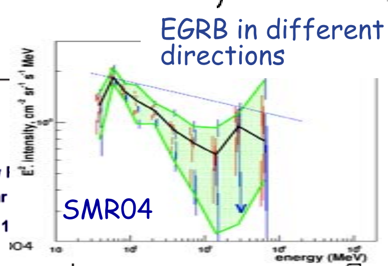
ψ -star formation rate

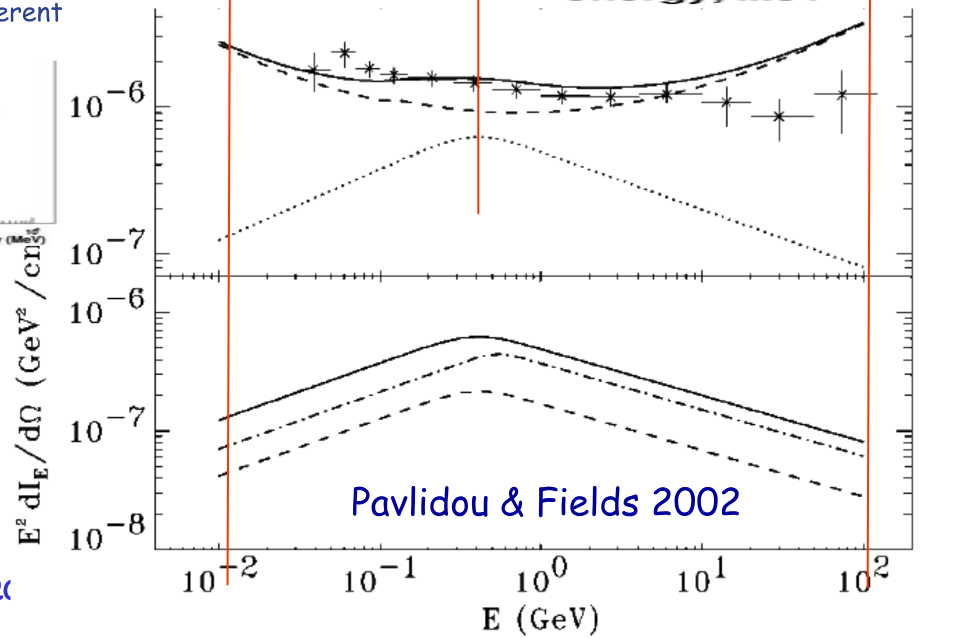
μ -gas mass fraction

$$\frac{dI_E}{d\Omega} = \frac{c}{4\pi H_0 \psi_{MW}} \int_0^{z_*} dz \left\{ \dot\rho_*(z) \frac{L_{\gamma,\,MW}[(1+z)E]}{\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}} \times \left[\frac{1}{\mu_{0,\,MW}} - \left(\frac{1}{\mu_{0,\,MW}} - 1 \right) \frac{\int_{z_*}^{z} dz (dt/dz) \dot\rho_*(z)}{\int_{z_*}^{0} dz (dt/dz) \dot\rho_*(z)} \right] \right\}.$$









What the Local Group Can Tell US?

- Further evidence that CR are galactic (not universal/extragalactic)
- Better understanding of the processes governing by the CR production and propagation in the MW and elsewhere
- More reliable predictions for starburst galaxies
- Study of the history of CR in other galaxies using Be,B observations in stars (chemical evolution)
- Estimates of the EG background from the normal galaxies (Cosmology, Cosmological DM etc.)
- Need targeted multi-wavelength observations or/and archive data
- Large diffuse emitters –we must have them in our diffuse background model !

That's it!