High energy processes in massive star forming regions and starburst galaxies

A.Marcowith (LPTA, Montpellier)

- Introduction:Starburst (StBs) versus AGN
- High energy phenomena in starbursts and massive star clusters.
- Connection to cosmic ray (CR) physics
- Conclusions & outlook.

Introduction

AGN

- Powered by a massive black hole

- Non-thermal objects
- $L = 10^{11}$-10^{13} $L_{\odot}$
- Highly variable flux

- AGN->SB:

-Triggering star formation?

Most of the talks in this workshop.

Starburst

- Powered by massive star winds and radiation.

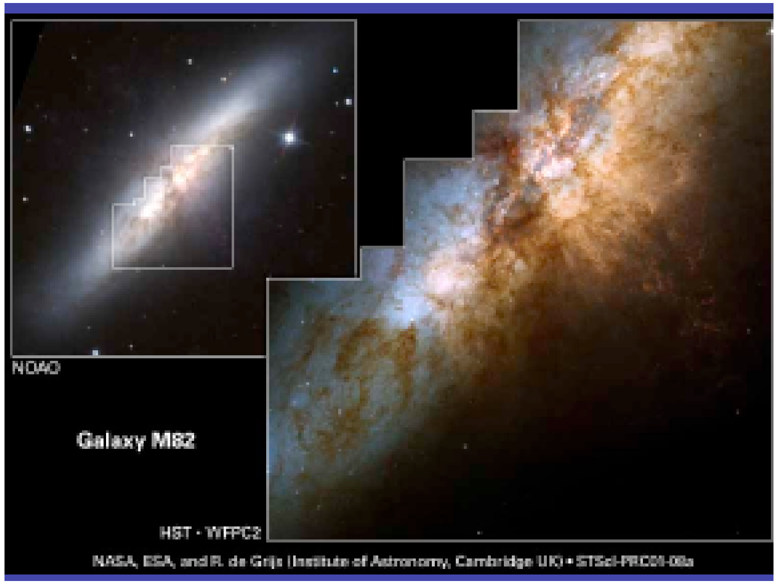
- (mostly) Thermal objects.
- $L = 10^{10}$-10^{12} $L_{\odot}$.
- Non variable flux.

- SB-> AGN:

-Feeding the central BH

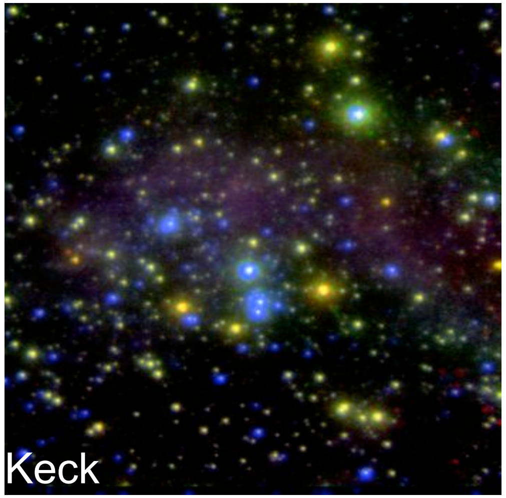
-Massive star explosions->BH merging.

Examples of starburst galaxies (SBG)



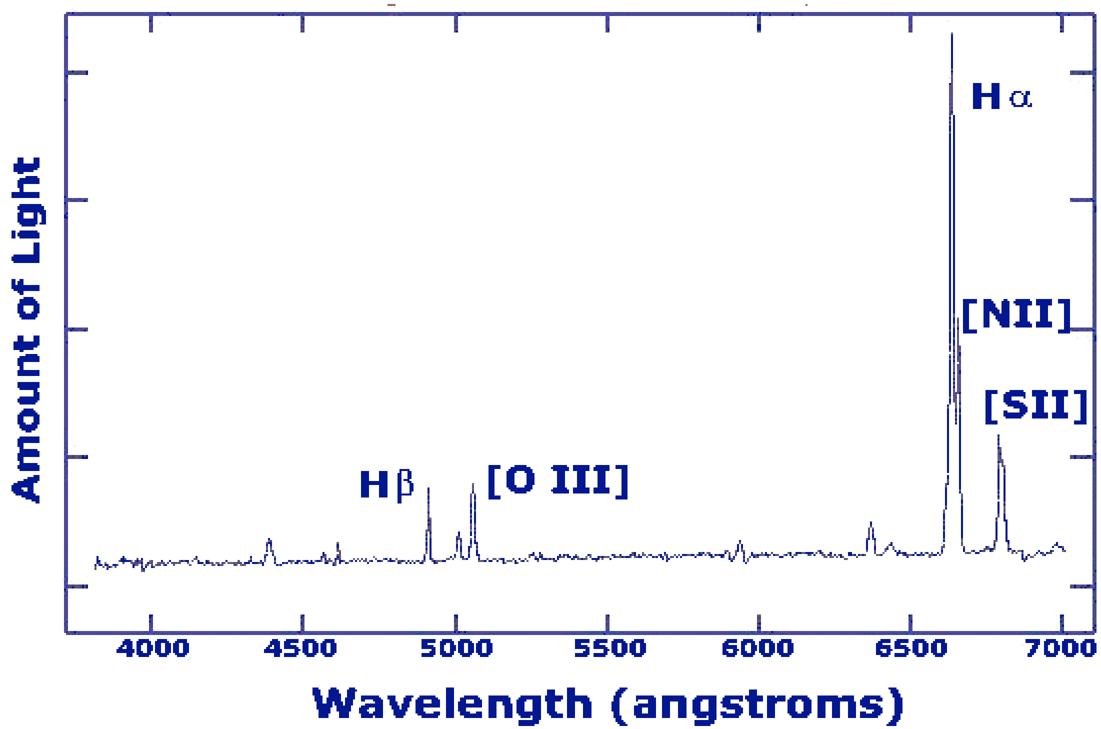
Hubble: green
Chandra: blue
Spitzer: red

- M82: Irregular galaxy
  D~3 Mpc
  SFR = 10 x SFR_{MW}



- IC 10: irregular galaxy
  D~700 kpc
  Very high rate of Wolf-Rayet stars: 5 stars/kpc^2 (~2x LMC)

Starburst Galaxy Spectrum



- Multiple HII region: Ionised hydrogen + excited ion lines

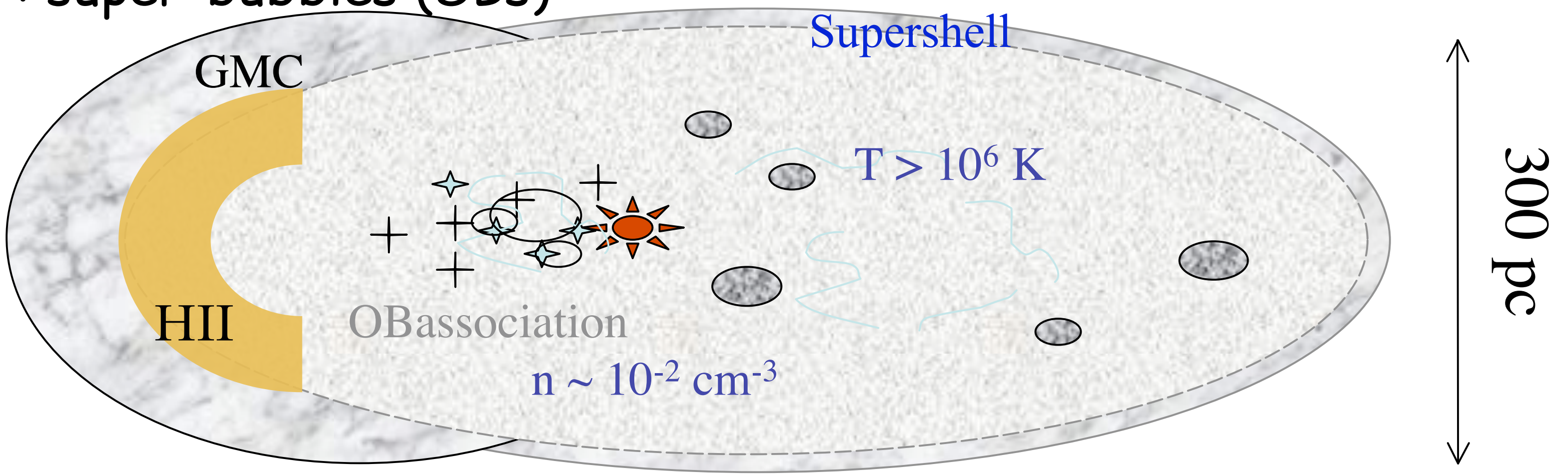
e- + H, He, O, S -> $H_{\alpha,\beta}$ recombinaison lines

-> OIII, NII, SII forbidden lines

- Produce huge IR dust radiation (reprocessed UV light): 10^{10-12} $L_{\odot}$
- Strong radio continuum emission which correlates with L_{IR} (de Jong et al'85)

"Starburst" in the milky way (and local galaxies)

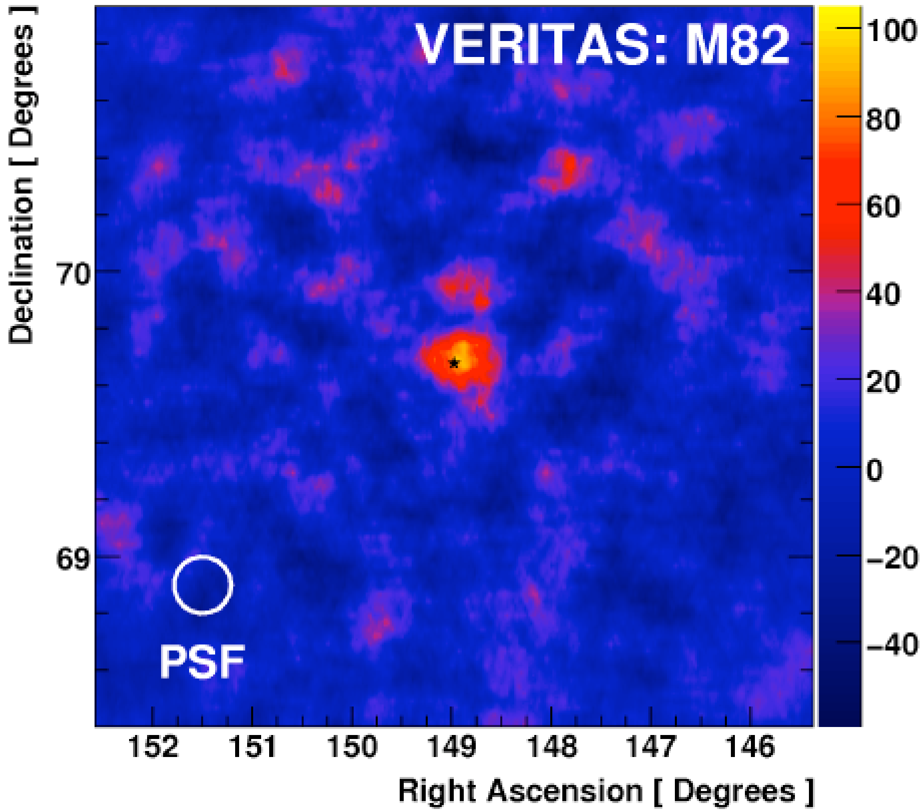
• Collective winds (OB association) + SN explosion => hot & low density plasma : super-bubbles (SBs)



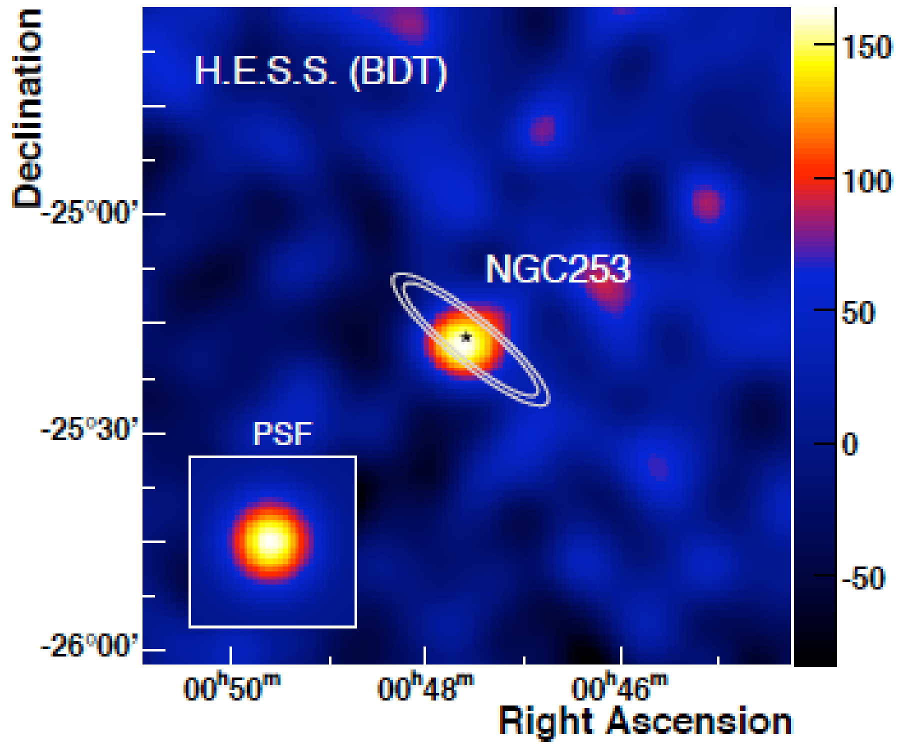
- Several young clusters close to the GC: 10% star formation activity in the MW: central cluster, quintuplet cluster, arches cluster (Figer'08).

	Age (Myr)	O	LBV	WN	WC	RSG
Quintuplet	4	100	2	6	11	1
Arches	2	160	0	$\gtrsim$6	0	0
Center	4–7	100	$\gtrsim$1	$\gtrsim$18	$\gtrsim$12	3
Total		360	$\gtrsim$3	$\gtrsim$29	$\gtrsim$23	4

Gamma-ray radiation from starburst galaxies



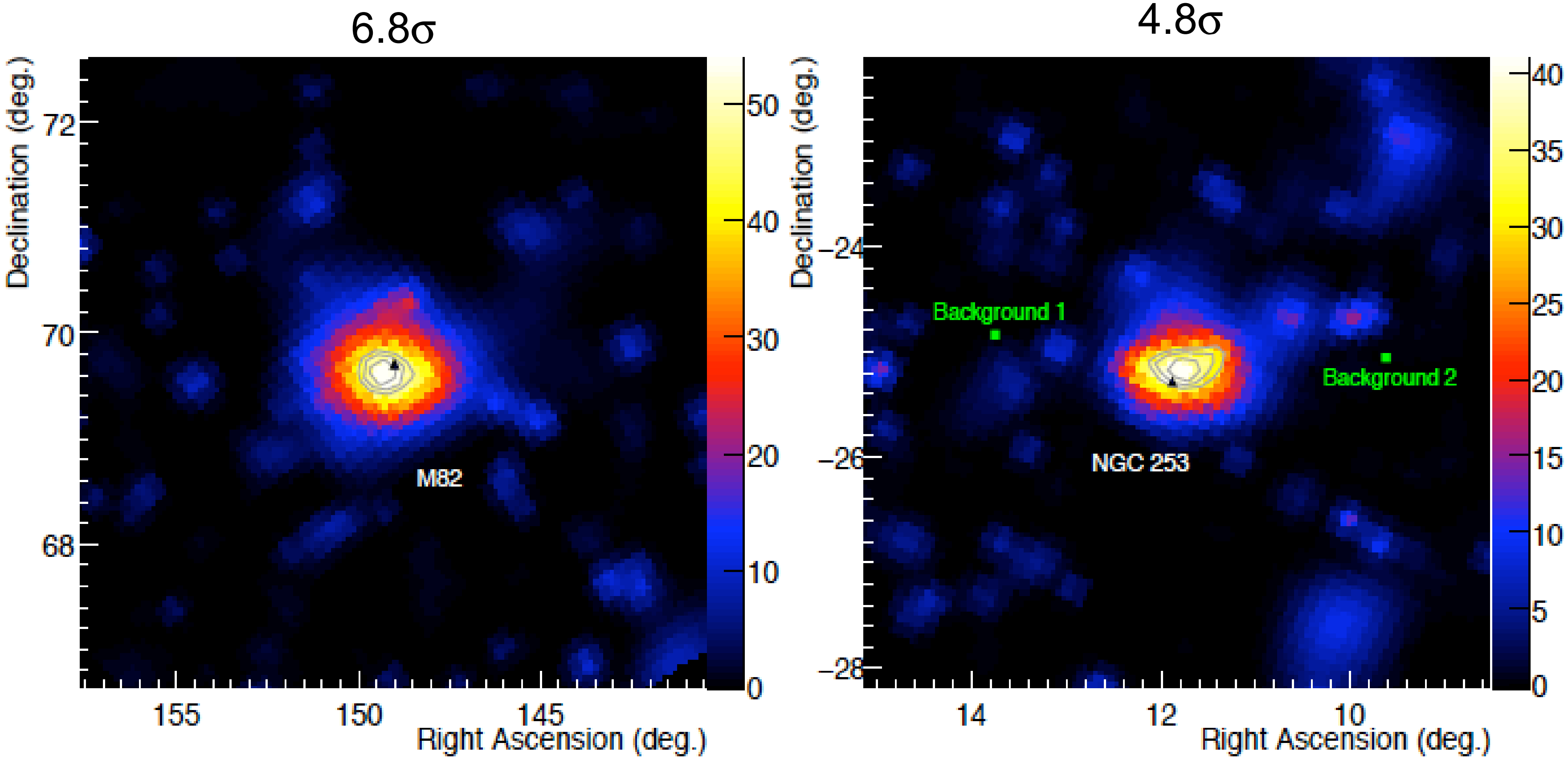
Acciari et al'09



Acero et al'09

Fermi observations

- Detection of M82, NGC253 Abdo et al'09



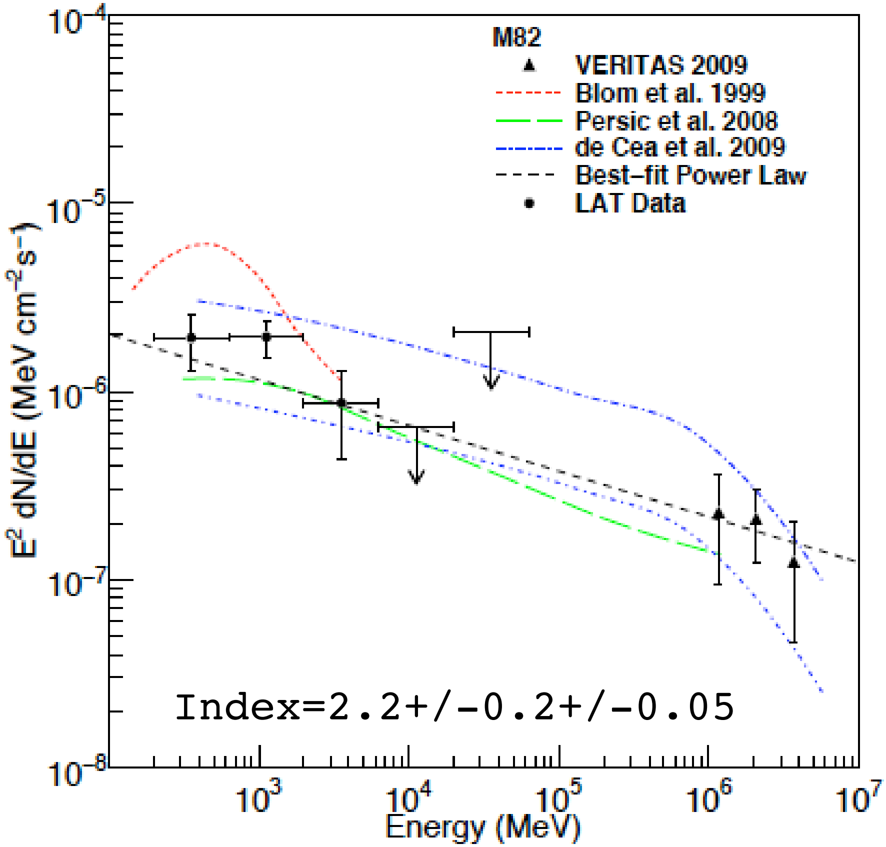
Black triangles: optical positions

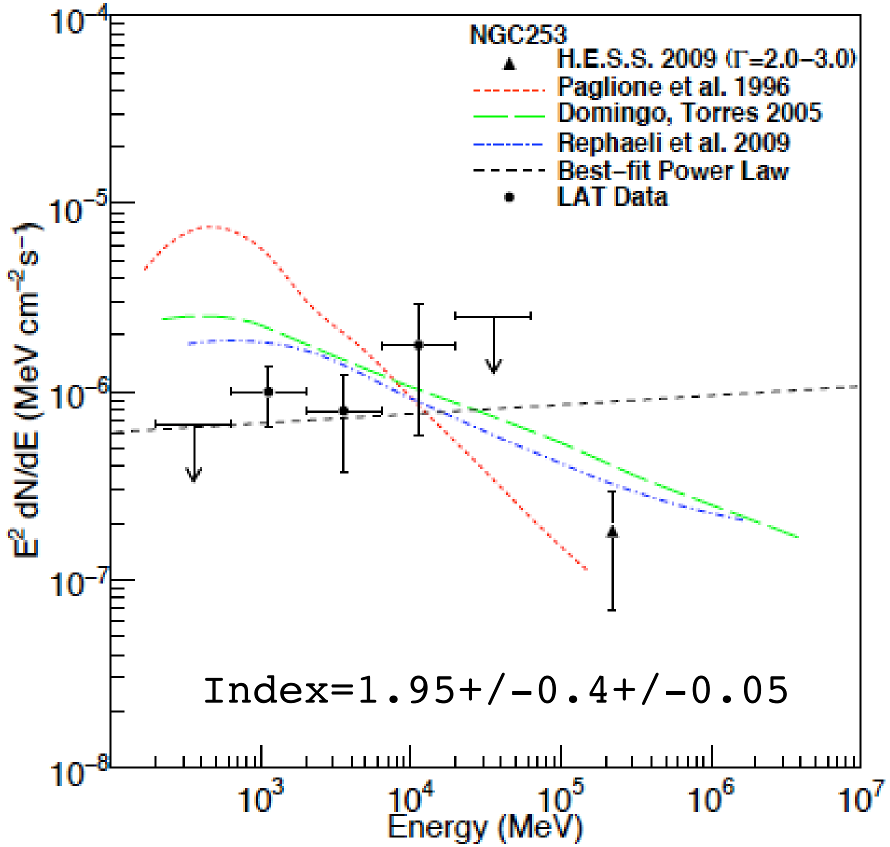
Map 6°x6°

Contours: 1, 2, 3σ

Gamma-ray spectra

Abdo et al'09





No variability reported

Fermi-Veritas: Compatible with one power-law and one emission mechanism: E_{cr}~250 eV/cm³ more than 200 x E_{MW}

No variability reported

Hard spectrum Fermi-Hess: softening.

Massive star forming regions (MSFR): diffuse X-rays 1

- Diffuse X-ray emission <=> Number of massive stars

TABLE 4

DIFFUSE X-RAYS FROM HIGH-MASS STAR FORMING REGIONS

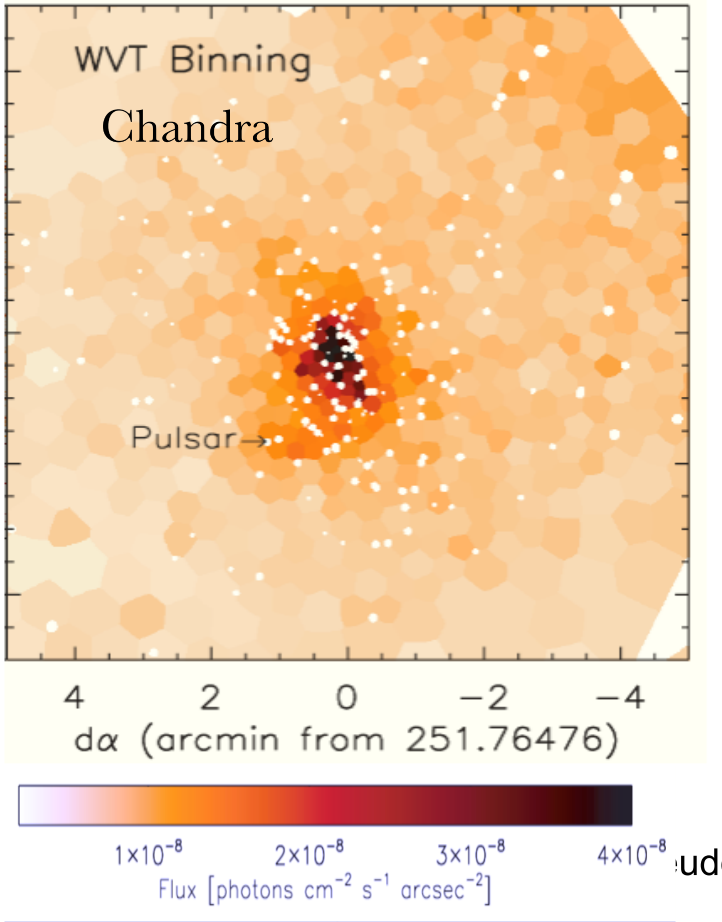
Region	Distance (pc)	Earliest Star[a]	Number O6 or Earlier	Diffuse X-Rays?	Diffuse Area (pc^2)	N_H (10^{21} cm^{-2})	kT (keV)	L_X[b] (10^{33} ergs s^{-1})
LMSFRs[c]	150–350	Late B	0	No	...	...	...	$\leq 10^{-5}$
Orion Nebula	450	O6	1	No	...	...	...	$<10^{-3}$
Eagle Nebula	2000	O5	2:	...	...	...	...	$<10^{-3}$
Lagoon, NGC 6530.......	1800	O4	3:	No	...	...	...	$<10^{-2}$
Lagoon, Hourglass	1800	O7	0	Probably	0.04	11.1	0.63	≤ 0.7[d]
Rosette Nebula	1400	O4	2	Yes	47	2	0.06, 0.8	≤ 0.6[d]
RCW 38	1700	O5	1:	Yes	2	11.5[e]	2.2[e]	1.6[e]
Omega Nebula[f]	1600	O4	7	Yes	42	4	0.13, 0.6	3.4
Arches cluster	8500	O3/W-R	>30	Yes	14	100	5.7	16
NGC 3603.....................	7000	O3/W-R	>20	Yes	50	7	3.1	20
Carina Nebula	2300	O3/W-R	>30	Yes	1270	3–40	0.8:	200:

Townsley et al '03

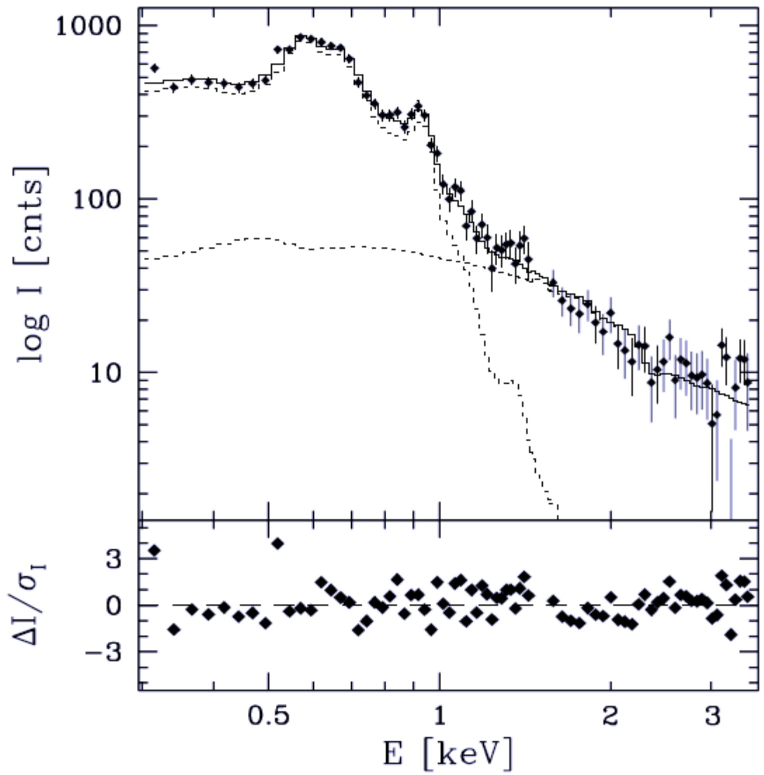
Diffuse X-rays 2

- Non-thermal X-rays (synchrotron/Bremsstralung)
  - Origin unclear: wind-wind interaction, SN remnants ?

Muno et al'06: Westerlund 1



Cooper et al'04: DEML192 (LMC)



XMM-Newton

Energy Crisis

- Input:
  - Stellar wind: E_{SW}
  - Supernovae: E_{SN}
- Output:
  - Thermal energy of the SB interior: E_{th} (> E_{NT})
  - Kinetic energy of the ionized/neutral supershell: E_{kinH} , E_{kinHI}

TABLE 2

ENERGY BUDGET OF THE SUPERBUBBLE DEM L192

Energies	Amount ($\times 10^{51}$ ergs)
E_{th} of the hot gas in superbubble interior	1.1 ± 0.5
E_{kin} of the ionized (H II) superbubble shell	1.5 ± 0.5
E_{kin} of the neutral (H I) superbubble shell	3.2 ± 0.5
Total energy observed in the superbubble	6 ± 2
Stellar wind energy input in 3 Myr	5 ± 1
Supernova energy input	13 ± 4
Total stellar energy input	18 ± 5

2/3 of the injected energy is missing

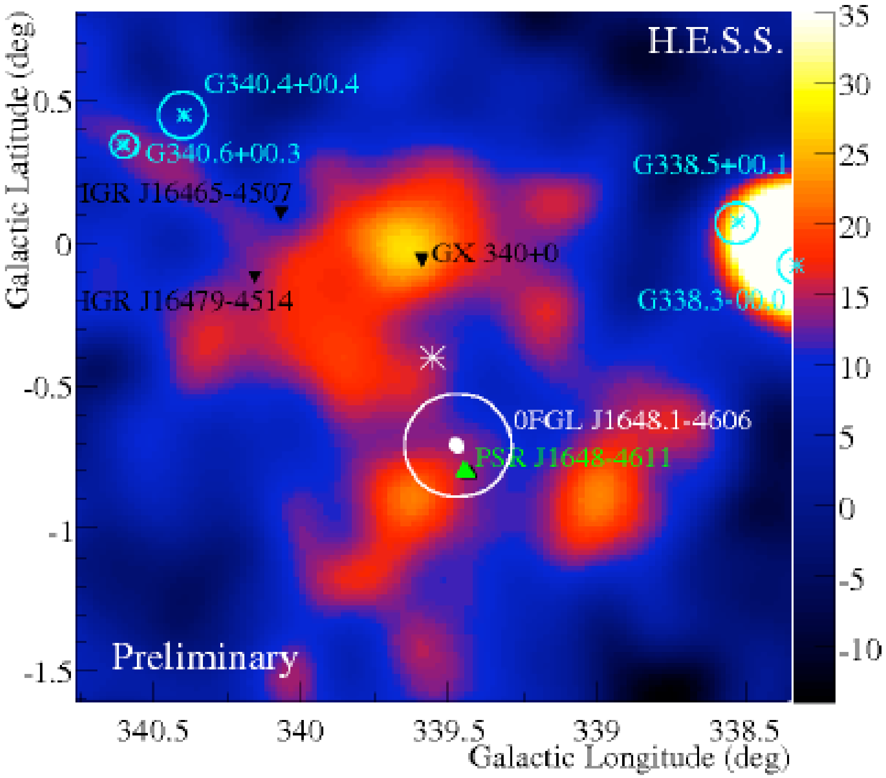
Cooper et al'04

Not the only case
- Thermal conduction ?
- Energetic particles ?

=> Cosmic rays ?

Galactic MSFRs & gamma-rays 1

- Cygnus OB2 (Hegra), Cygnus region (Milagro), Westerlund 1 & 2 (HESS)



Ohm et al'09

<u>Westerlund 1</u>:

N_{OB*} ~ 450

Core size ~ 0.5 pc

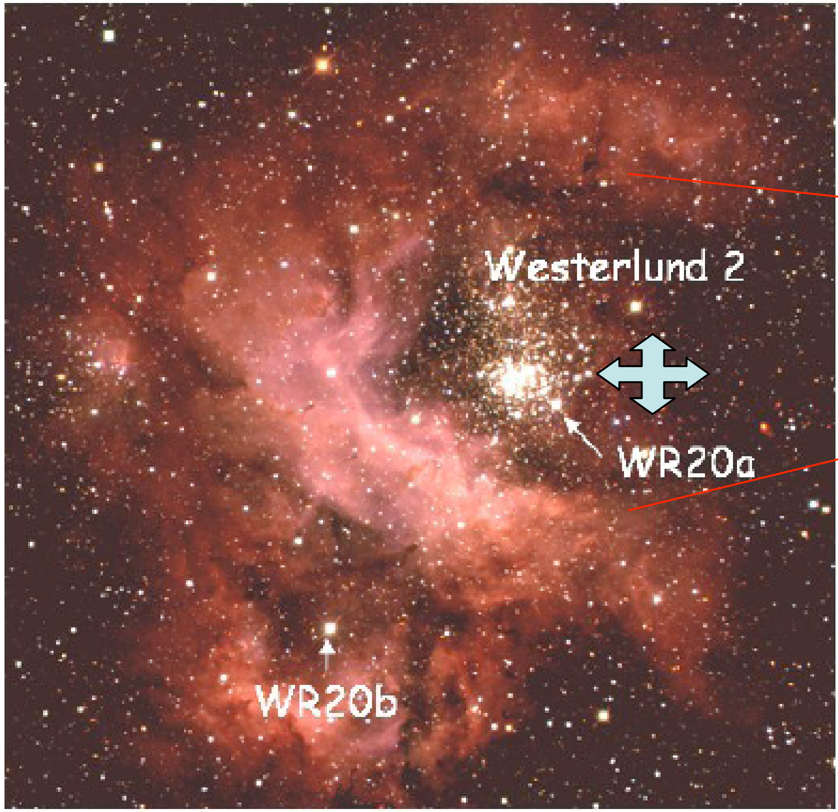
* Galactic cluster with the richest population of WR stars = 24

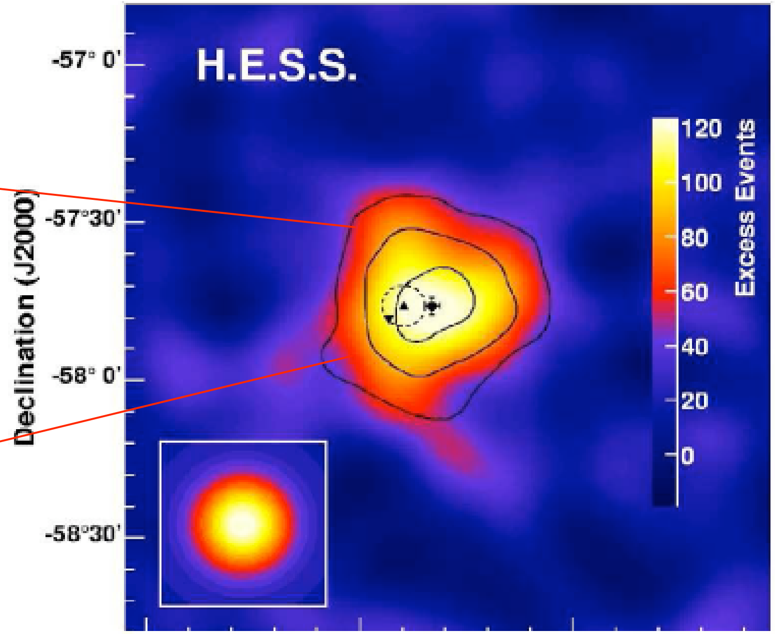
Gamma-ray emission: clearly extended.

Several counterparts (pulsar seen by Fermi, X-ray binary, SN remnants …)

…TBC…

Galactic MSFRs & gamma-rays 2





Westerlund 2 by HESS
Aharonian et al'07

Age ~2 M years
Distance ~8 kpc

WR20a: largest mass WR binary
N_{OB*}~14

Summary: Non-AGN gamma-ray galaxies

Summary: M82, NGC253

	RA[a] (deg)	Dec[a] (deg)	r^a_{95} (deg)	F(> 100 MeV)[b] (10^{-8} ph cm^{-2} s^{-1})	photon index[b]	significance[c]
M82	149.06	69.64	0.11	$1.6 \pm 0.5_{stat} \pm 0.3_{sys}$	$2.2 \pm 0.2_{stat} \pm 0.05_{sys}$	6.8
NGC 253	11.79	-25.21	0.14	$0.6 \pm 0.4_{stat} \pm 0.4_{sys}$	$1.95 \pm 0.4_{stat} \pm 0.05_{sys}$	4.8

Galaxy	d (Mpc)	R_{SN} (yr^{-1}) SN rate	M_{Gas} (10^9 $M_\odot$)	F_γ[a] (10^{-8} ph cm^{-2} s^{-1})	$4\pi d^2 F_\gamma$[a] (10^{42} ph s^{-1})	L_γ[a] (10^{39} erg s^{-1}) gamma-ray luminosity
LMC[b]	0.049 ± 0.001	0.005 ± 0.002	0.67 ± 0.08	26.3 ± 4.7	0.074 ± 0.013	0.041 ± 0.007
Milky Way[c]	1	0.02 ± 0.01	6.5 ± 2.0	4.6 ± 2.3	5.5 ± 2.8	3.2 ± 1.6
M82	3.6 ± 0.3	0.2 ± 0.1	2.5 ± 0.7	1.6 ± 0.5	25 ± 9	13 ± 5.0
NGC 253	3.9 ± 0.4	0.2 ± 0.1	2.5 ± 0.6	0.6 ± 0.4	11 ± 7	7.2 ± 4.7

+ No variability

Abdo et al'09

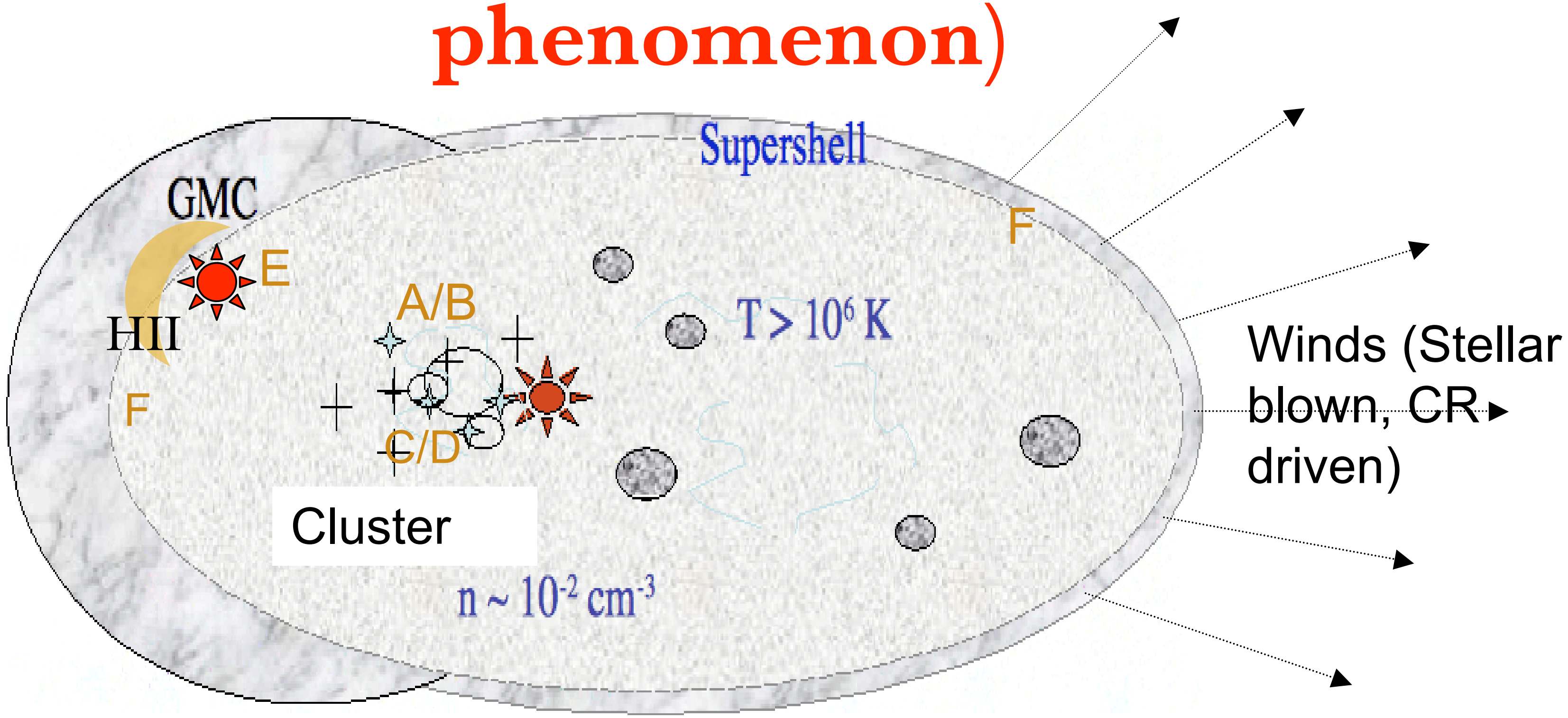
Open issues

- L_γ seems to scale with R_{SN} (although not linearly)

SN => particle acceleration, turbulence injection…

1. Sources of free energy ?
2. Emission mechanisms ?
3. Contribution to cosmic ray spectrum ?

-1- Sources (connected with SN phenomenon)



- Scenario A/B: Isolated/binary stars Völk & Forman'82, Usov & Eichler'93
- Scenario C/D: Collective winds with internal/external accelerator Klepach et al'00, Parizot, A.M. et al'04, Domingo-Santamaria & Torres'06
- Scenario E: SNr/Molecular cloud interaction Bykov et al'00
- Scenario F: EP interaction with shells/Clouds Bykov & Fleishmann'92

-2- Emission mechanisms: The GeV-TeV connection

- Different possibilities: Inverse Compton, Bremsstrahlung, neutral pion.
- One way to disentangle upon the different scenarii in the Fermi / HESS and then HESSII/CTA era.
- one example …

Starburst emission

- <u>Phenomenological approach</u>:

  L_{radio}, s_{radio}, L_X <=> Synchrotron

  L_{CO}, L_{IR} <=> density, SN rate: $R_{SN}=2.3\times10^{-12}\ L_{IR}/L_{\odot}\ yr^{-1}$ (Chevalier'82)

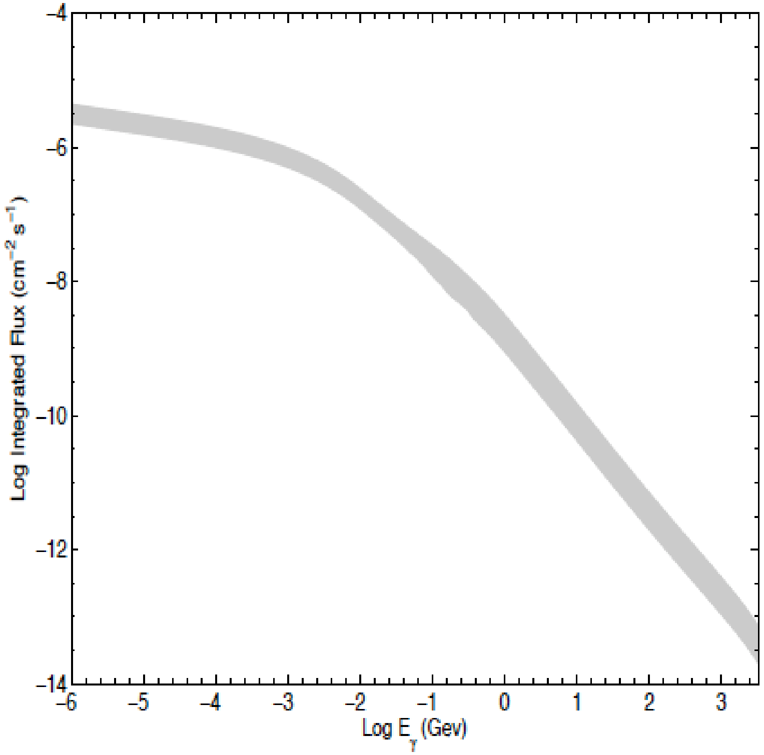
  L_{IR}, L_{gamma} <=> Inverse Compton, K_{ep}, ξ_{CR}

  Transport: leaky-box model

Rephaeli et al'10

Consistent with Fermi & Veritas data on M82: [F(>100 MeV) = 2×10^{-8} ph/cm^{2}s, S=2.3]

- Dominated by neutral pion decay
- Requires B~190 μG in the central region.



-3- Link to cosmic rays

- Starbursts/MSFRs are relevant for many aspects: Galactic and extragalactic CRs.
  - Enhanced SF rates; hence SN explosion rate (up to R_{MW}x10).
  - High energy emitters; hence (possibly) CR accelerators.
  - Local strong sources of CRs; hence drive strong galactic shocks (Zirakashvili et al '96)
  - Enhanced SN explosion rate; hence GRB rate (Becker et al'09)

- Galactic MSFRs/Superbubbles are relevant as well: Galactic CRs.
  - Collective effects of massive star winds, maximum energy of the galactic component ? (Parizot et al'04)
  - Wolf-Rayet ejecta enrichment, CR composition anomalies (Higdon et al'05)

- CR spectrum : beyond phenomenology.

SNOB/SB model

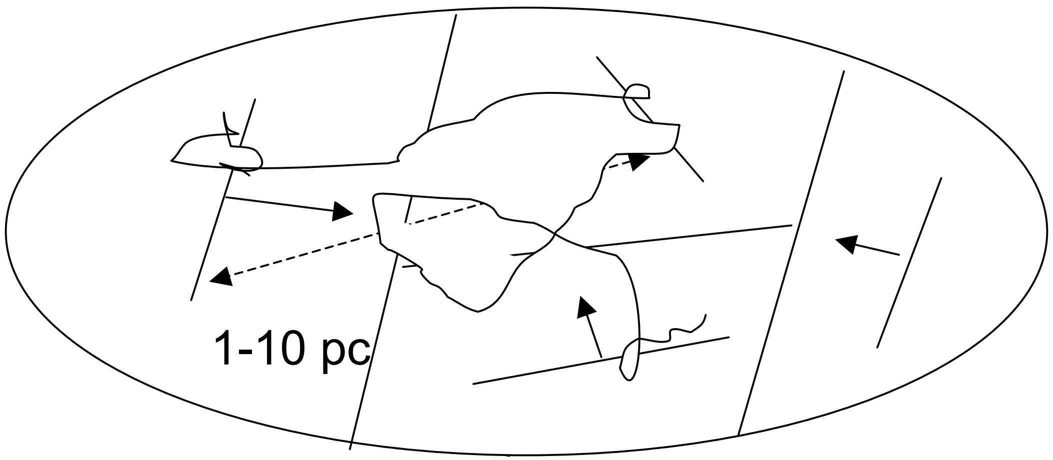
<u>MSFR & SB regions</u>:

- Sure: Multiple SN explosions + Stellar winds (Montmerle'79)
- Depending on the degree of inhomogeneity: Weak secondary (low Mach number) reflected shocks (Parizot et al'04)

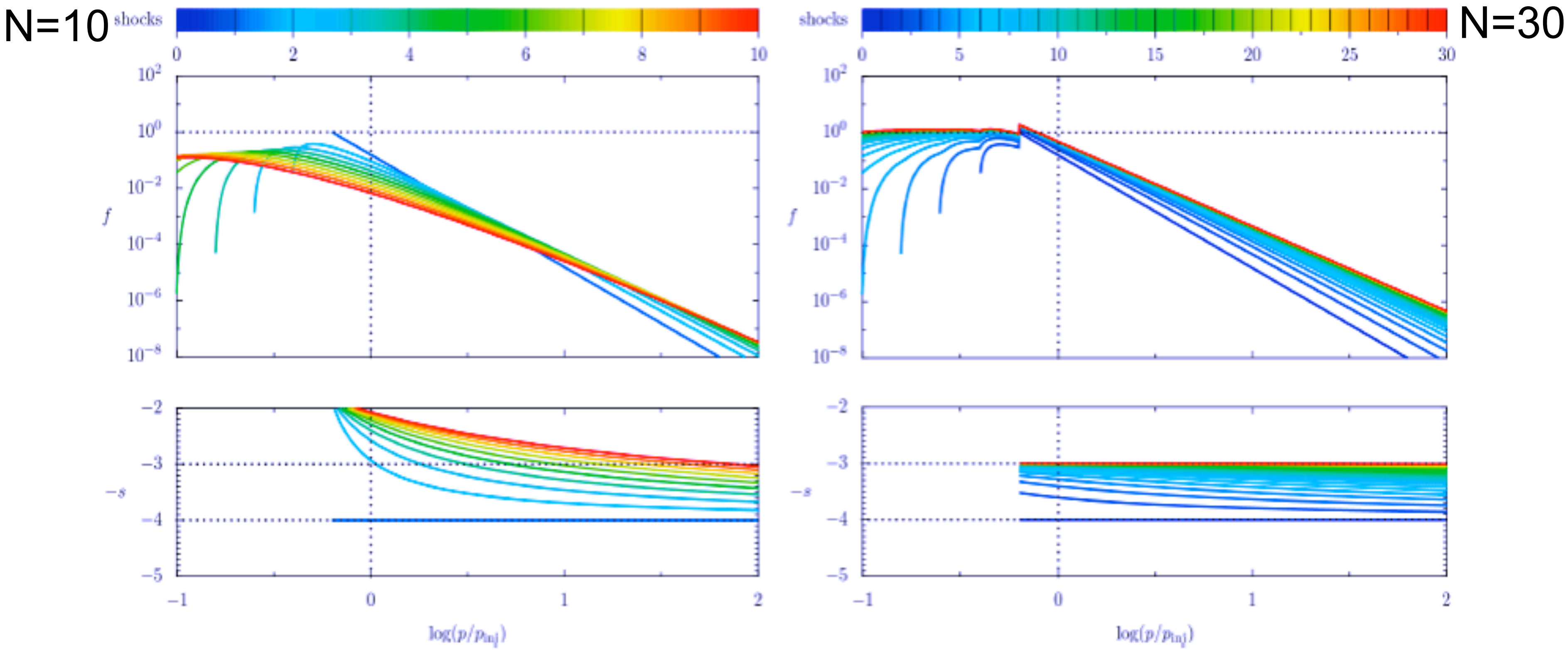
- Random SNR explosions + weak shock sample

⇨ Non-equilibrium highly intermittent particle distribution.

- Semi-analytical calculations:
  - Particle distribution evolves under several effects: FI, FII, spatial escape, large scale turbulence ….



Multiple shock acceleration



Acceleration
+ Decompression

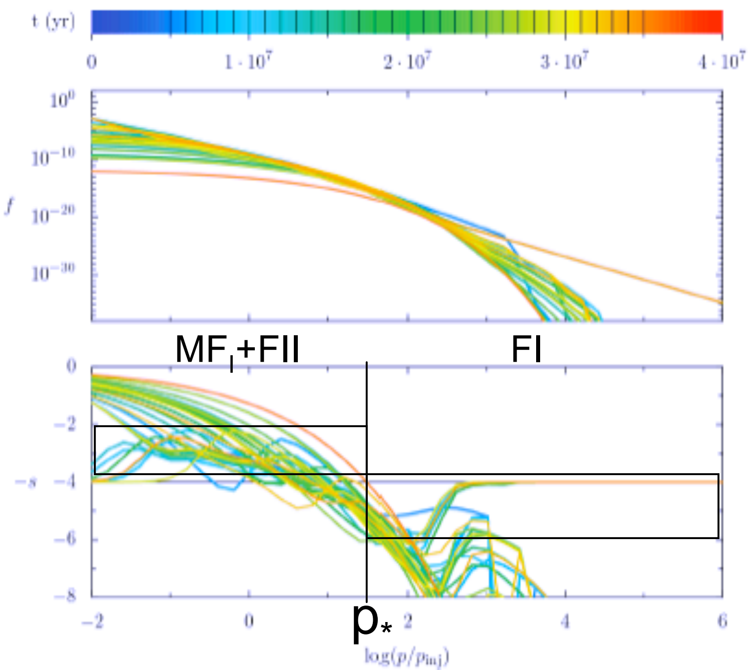
$$f_{(i)}(p) = \frac{k\, s_1^i}{p_{\rm inj}} \left(\frac{R^i\, p}{p_{\rm inj}}\right)^{-s_1} \frac{\left(\ln\left(\frac{R^i\, p}{p_{\rm inj}}\right)\right)^{i-1}}{(i-1)!} H\left(p - \frac{p_{\rm inj}}{R^i}\right)$$

$$f_n(p) = \sum_{i=1}^{n} f_{(i)}(p) \qquad f_\infty(p > p_{\rm inj}) \propto p^{-3}$$

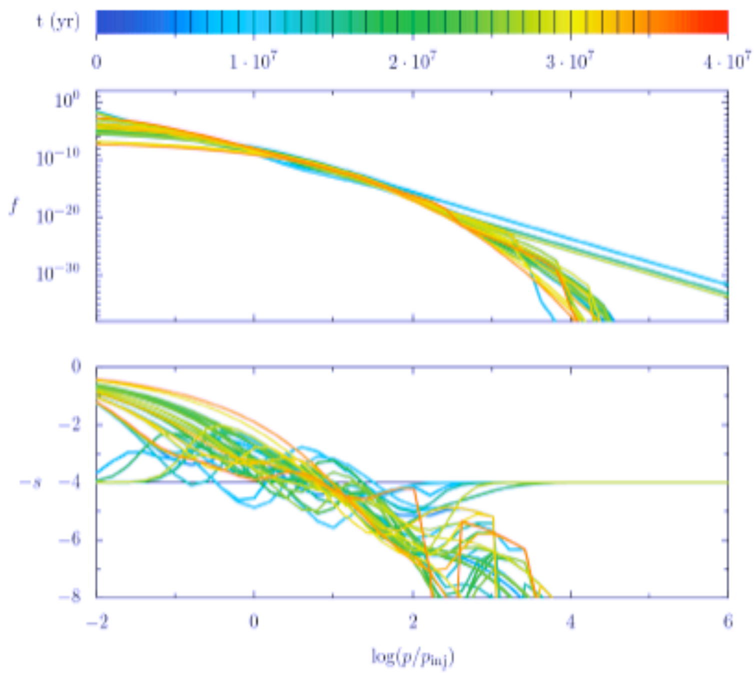
Melrose & Pope'93

Test particle solutions 1

- Particle evolution: $G_{FI} \otimes G_{FII}$ (Achterberg'90, Ferrand & A.M.'09)
- SN explosion sampled over Salpeter IMF: $t_{FI} < \Delta t_{SN} = 10^{5\text{-}6}$yr
- Turbulence model; e.g. isotropic Kolmogorov => FII and spatial escape during Δt_{SN}



1000 stars in: 100 clusters of 10 stars

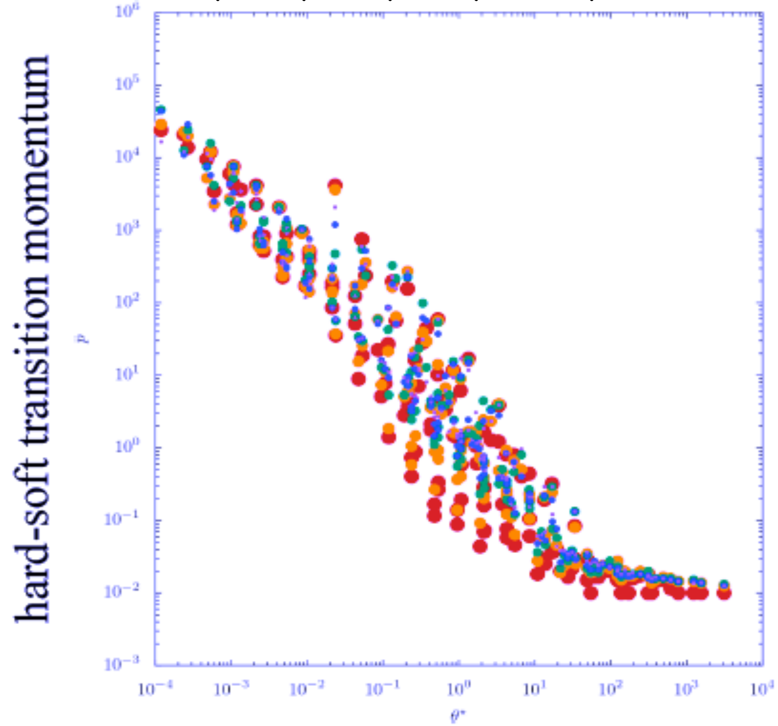


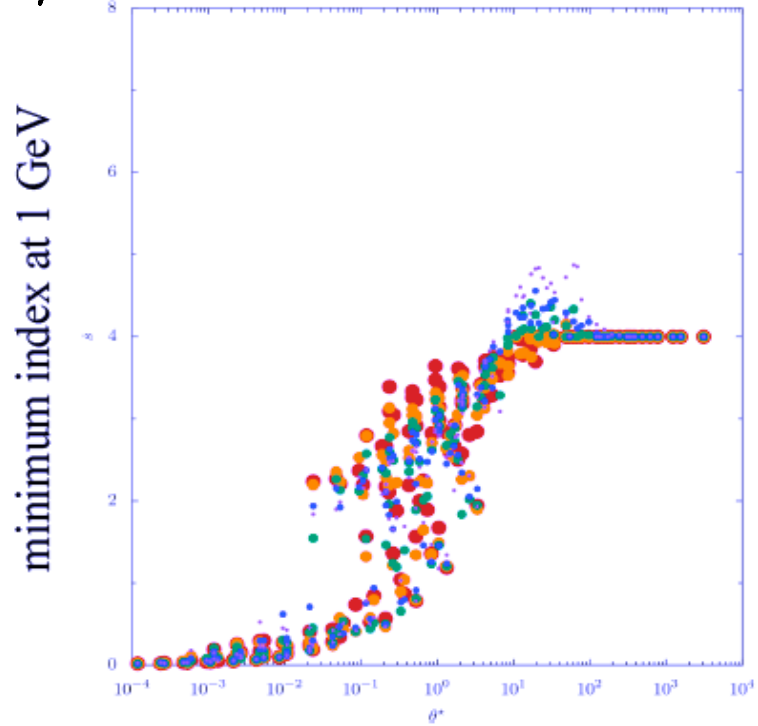
10 clusters of 100 stars

Parametric studies

$N_\star$=10, 20, 30, 70, 200, 500: coded by size and color

Ferrand & A.M.'09





many physical parameters, often poorly constrained → 720 runs

$N_\star = [10, 30, 70, 200, 500]; \; r = 4$

$B = [1, 10]\,\mu\mathrm{G}; \; \eta_T = [1/5, 1]; \; q = [3/2, 5/3]; \; \lambda_{\max} = [10, 20, 40, 80]\ \mathrm{pc}$

$n = [10^{-3}, 5.10^{-3}, 10^{-2}]\ \mathrm{cm}^{-3}; \; x_{\mathrm{acc}} = [40, 80, 120]\ \mathrm{pc}$

m c/p$_\star$ ~ $\theta^\star = (D_p^\star\, t_{\mathrm{esc}}^\star)^{-1} \in [10^{-4}, 10^{+4}]$

Ferrand & A.M.'09

Sample of galactic and LMC SBs

	Cluster				Superbubble		$\theta_\star$			
Name	$N_\star$	Age (Myr)	Distance (kpc)	Size (pc)	Size (pc)	Density (cm^{-3})	B=1μG $q=5/3$	B=1μG $q=3/2$	B=10μG $q=5/3$	B=10μG $q=3/2$
Cygnus OB1/3	38[16]	2-6[12]	1.8[19]	24	80-100[14]	0.01?	5.10^4 5.10^5	4.10^2 3.10^3	4.10^0 4.10^1	2.10^{-2} 1.10^{-1}
Cygnus OB2	750[5]	3-4[12]	1.4-1.7[10]	60[11]	450?[5]	0.02[5]	2.10^4 2.10^5	9.10^1 7.10^2	1.10^0 2.10^1	4.10^{-3} 3.10^{-2}
Orion OB1	30-100[3]	12[2]	0.45[2]	10[2]	140x300[3]	0.02-0.03[4]	3.10^3 2.10^6	4.10^1 7.10^3	3.10^{-1} 2.10^2	1.10^{-3} 3.10^{-1}
Carina nebula	?	3[23]	2.3[8]	20	110[23]	0.01?	2.10^4 2.10^6	1.10^2 7.10^3	1.10^0 1.10^2	5.10^{-3} 3.10^{-1}
Westerlund 1	450[1]	3.3[1]	3.9[13]	1[1]	40?[13]	0.01?	2.10^3 3.10^6	5.10^1 2.10^4	2.10^{-1} 3.10^2	2.10^{-3} 8.10^{-1}
Westerlund 2	14[21]	2[21]	8[21]	1[6]	100[21,6]	0.0015[24]	1.10^2 5.10^4	2.10^0 2.10^2	9.10^{-3} 4.10^0	1.10^{-4} 1.10^{-2}
DEM L192	135	3[20]	50	60[20]	120x135[9]	0.03[7]	3.10^5 1.10^6	2.10^3 4.10^3	2.10^1 9.10^1	6.10^{-2} 2.10^{-1}
30 Doradus	> 400[22]	2[17]	50	40[25]	200[25]	0.09[27]	2.10^5 2.10^6	1.10^3 7.10^3	2.10^1 2.10^2	6.10^{-2} 3.10^{-1}
N11	130	5[26]	50	15x30[18]	100x150[9]	0.08[15]	9.10^4 4.10^6	9.10^2 2.10^4	8.10^0 4.10^2	3.10^{-2} 8.10^{-1}

- Parameter $\theta_\star$ (~$mc/p_\star$) is usually >> 1: transition to s=3 deep in the non-relativistic regime except (B=10,q=3/2, 5/3) high B= turbulent dynamo; e.g. Bykov & Toptyghin's regime.

⇒Strong non-linear back reaction not as usual as expected (conversly to isolated SNRs).

$$\theta^\star \simeq \begin{cases} \frac{2}{\eta_T^2}\left(\frac{B}{10\,\mu\mathrm{G}}\right)^{-\frac{8}{3}}\left(\frac{\lambda_{\max}}{10\,\mathrm{pc}}\right)^{\frac{4}{3}}\left(\frac{x_{\mathrm{acc}}}{40\,\mathrm{pc}}\right)^{-2}\left(\frac{n}{10^{-2}\,\mathrm{cm}^{-3}}\right) & q=5/3 \\ \frac{10^{-2}}{\eta_T^2}\left(\frac{B}{10\,\mu\mathrm{G}}\right)^{-3}\left(\frac{\lambda_{\max}}{10\,\mathrm{pc}}\right)\left(\frac{x_{\mathrm{acc}}}{40\,\mathrm{pc}}\right)^{-2}\left(\frac{n}{10^{-2}\,\mathrm{cm}^{-3}}\right) & q=3/2 \end{cases}$$

Non-linear strong shock acceleration

- Non-linear sequence of strong shock waves (Ferrand et al'08)
- Final spectrum depends on the balance between "external" and "internal" injection rates.
  - Internal: thermal pool
  - External: pre-existing CRs (Blasi'04)

⇒ Specificity of SB modeling.

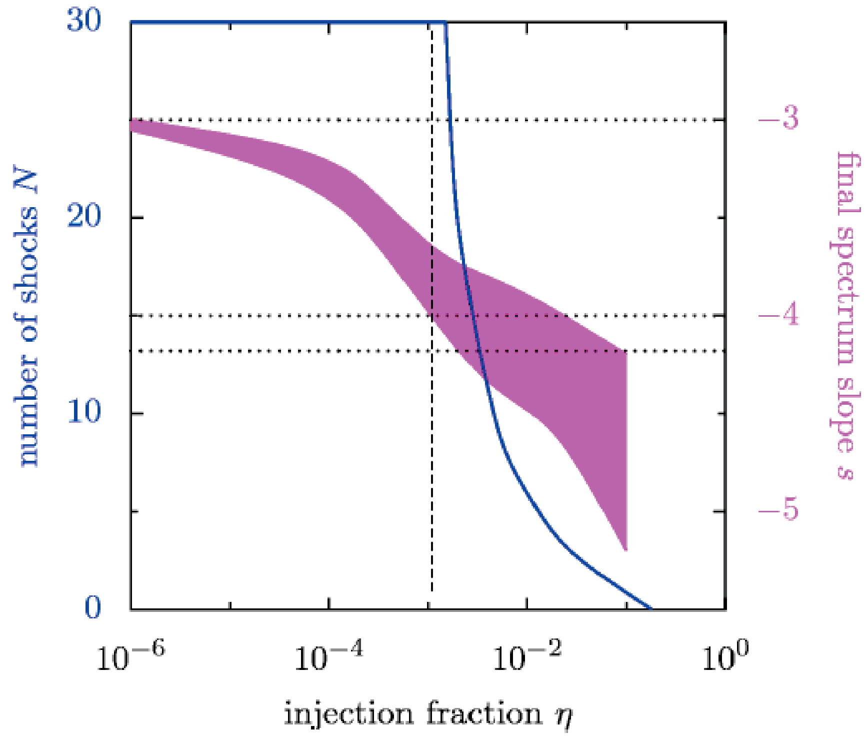
M_s=50 internal injection

M_s=5 external injection; weak shock reaccelerate

- More realistic simulations include the effect of θ_* (Ferrand & A.M in prep)

Index of the source spectrum

M_s=50



Test particle solutions 2

Bykov & Toptyghin: turbulent dynamo case [Bykov & Toptyghin '93]

- Ensemble average over large scale MHD turbulent motions + shocks (akind of *Fermi 1.5 process)* + stochastic acceleration on small scale (M)HD turbulence: shock turbulence

- Depends on the ratio $\zeta = (V L)/\kappa$:

  $\kappa = v\, l/3$; l = particle mean free path due to interaction with *small scale MHD* waves.

  $V = \langle u^2 \rangle^{1/2}$: mean fluid velocity.

  L = mean distance between two shocks; main turbulence scale.

⇨ $\zeta < 1$: Weak turbulence; perturbative theory

⇨ $\zeta > 1$: Strong turbulence; renormalised field theory.

Non-linear solutions: highly turbulent case

Spatial diffusion — Momentum transport (incl. snd order) — Injection

$$\frac{\partial N}{\partial t} - \frac{\partial}{\partial r_\alpha}\chi_{\alpha\beta}\frac{\partial N}{\partial r_\beta} = G\hat{L}N + \frac{1}{p^2}\frac{\partial}{\partial p}p^4 D\frac{\partial N}{\partial p} + A\hat{L}^2 N + 2B\hat{L}\hat{P}N + Q(p)$$

$$\hat{L} = \frac{1}{3p^2}\frac{\partial}{\partial p}p^{3-s}\int_0^p dp'\,p'^s\frac{\partial}{\partial p'}, \quad \hat{P} = \frac{p}{3}\frac{\partial}{\partial p}.$$

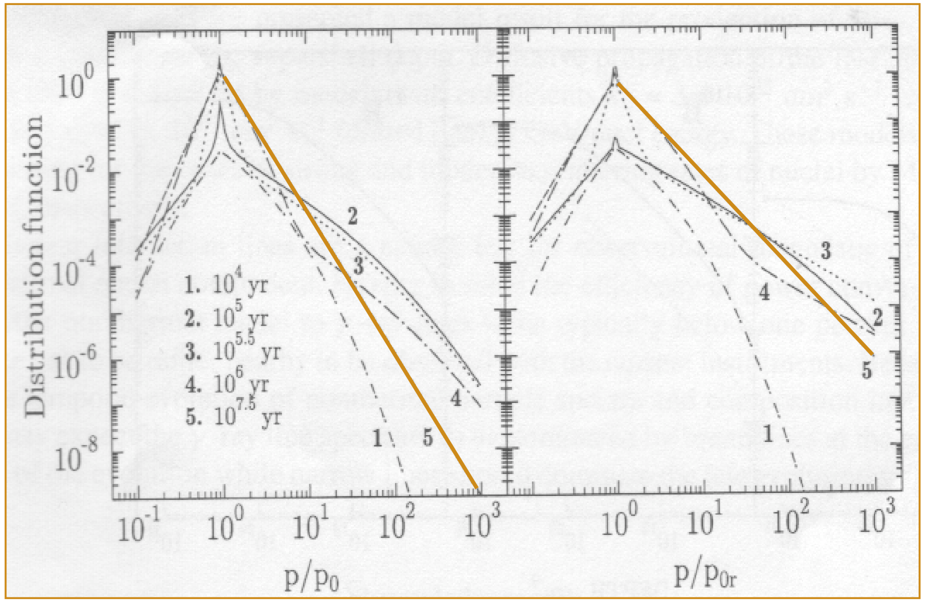
- L and P describe the effect of shock acceleration and adiabatic expansion of large scale ~~(M)~~HD flows over the particle momentum

[Bykov & Toptyghin '93]

A, B, G, c, D kinetics coefficients all functions of the turbulence spectrum (S,T). In case of homogeneous & isotropic turbulence:
$\langle \delta u_\alpha \delta u_\beta \rangle = T(k,\omega)\,(\delta_{\alpha\beta} - k_\alpha k_\beta/k^2) + S(k,\omega)\,k_\alpha k_\beta/k^2$

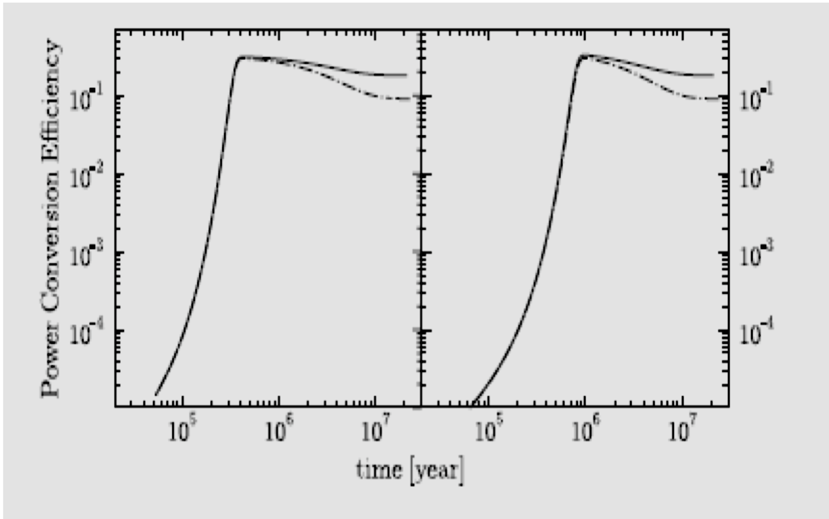
In this model: $p_*(t)$ increases with time so NL calculations are always mandatory

Source spectrum



Highly intermittent spectrum.

Bykov '01



Top-Heavy IMF Salpeter IMF

~ 30% of the energy imparted in the turbulence converted into NT particles within $\tau < 3$ Myr => young clusters & energy crisis issue

Maximum Galactic CR energy

- Galactic sources: $E_{max} = 10^{17}$ eV for protons => 2.6 10^{18} eV for Iron.
- One caveat of the standard SNR model: E_{max} including MF amplification ~ 10^{15} eV (Parizot, A.M. et al'06, A.M. et al'06)
- Possible remedies:
  - Acceleration above the CR knee at very early stages of SNR evolution (Bell'04, Ptuskin & Zirakashvili'05, Zirakashvili & Ptuskin'08)
  - Reacceleration in the galactic wind (termination shock, spiral shocks) (Ptuskin et al'97, Völk & Zirakashvili'04)
  - SN evolve differently in a SB:
    - no radiative phase.
    - Adibatic phases lasts longer.
  - Hillas criterium applied to SNRs in SBs with an amplification factor of the MF of A

  $E_{max} = Z \times (1.7 \times 10^{17}\text{eV})\ (A/20)\ (B_{SB}/10\mu G)$ (Parizot et al'04, Ferrand & A.M. in prep)

Starburst and UHECRs

- Two steps scenario:
  - Step 1: Acceleration by SNR (see previous slide)
  - Step 2: Transport in the superwind and re-accelerated at a galactic shock.

- Estimation (Torres & Anchordoqui'04) $E_{max} > 3 \times 10^{20}$ eV (NGC 253).

✓ Most optimistic case <=> perpendicular diffusion.

✓ No hint for correlation of Auger events with StBs galaxies catalogue (Abraham et al'08)

✓ In StBs $V_{T\text{-}sh} > 1000$ km/s, and $M_a > 1$ (fit in the Hillas plot)

=> SN MF amplification of non-resonant and resonant streaming modes could work there as well (Pelletier et al'06)

Conclusions

- Clusters of massive stars are gamma-ray emitters: NGC 253, M82 => TeV-PeV particles.
- Also in our Galaxy & LMC: Westerlund 1/2…probably more with CTA.
- But not all MSFRs (e.g. Carina nebula)

⇒ What are the sources of free energy ?

⇒ What are the emission mechanisms

  - GeV-TeV observations can bring some insights.

⇒ What are the conditions for high energy particle production ?

  - High turbulence level is required to confine particles.
  - But in that case non-linear back-reaction effects + intermittent spectrum.

- May explain larger maximum CR energies … TB still investigated.

- Supplementary material.

High energy particles & radiation at the core of the star formation process

Völk et al SSR 1996

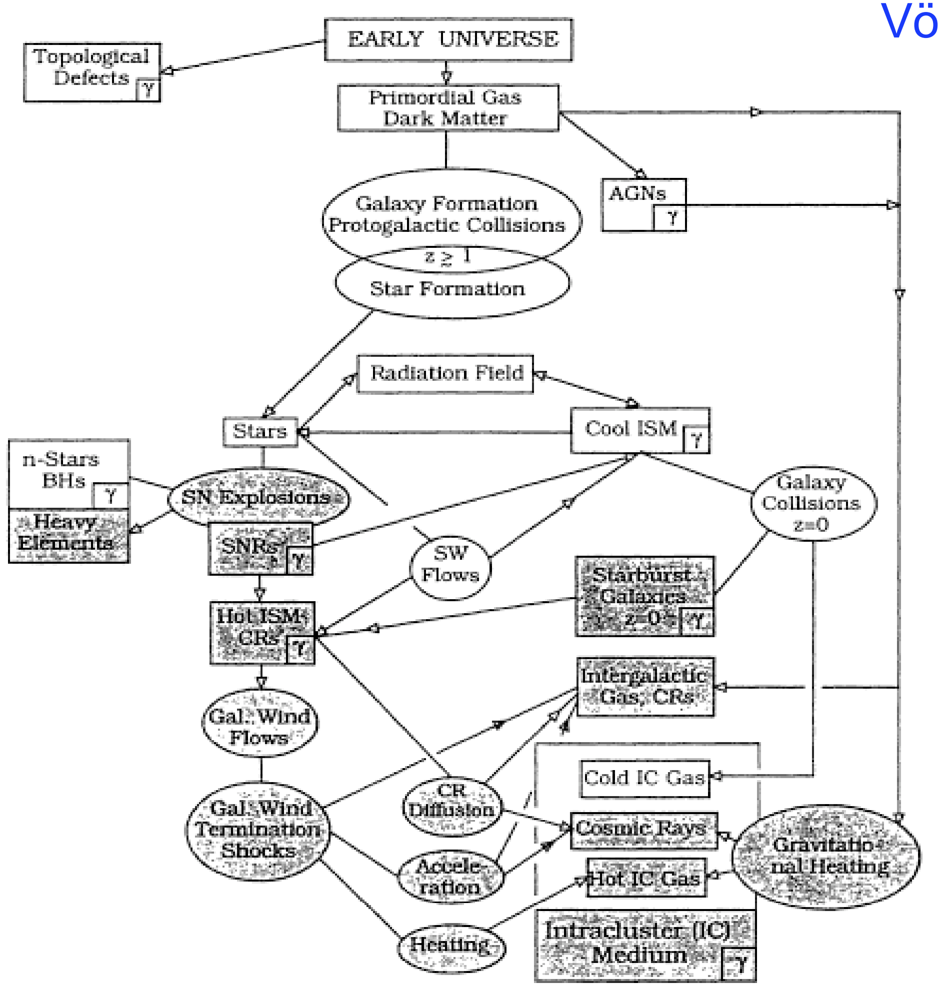
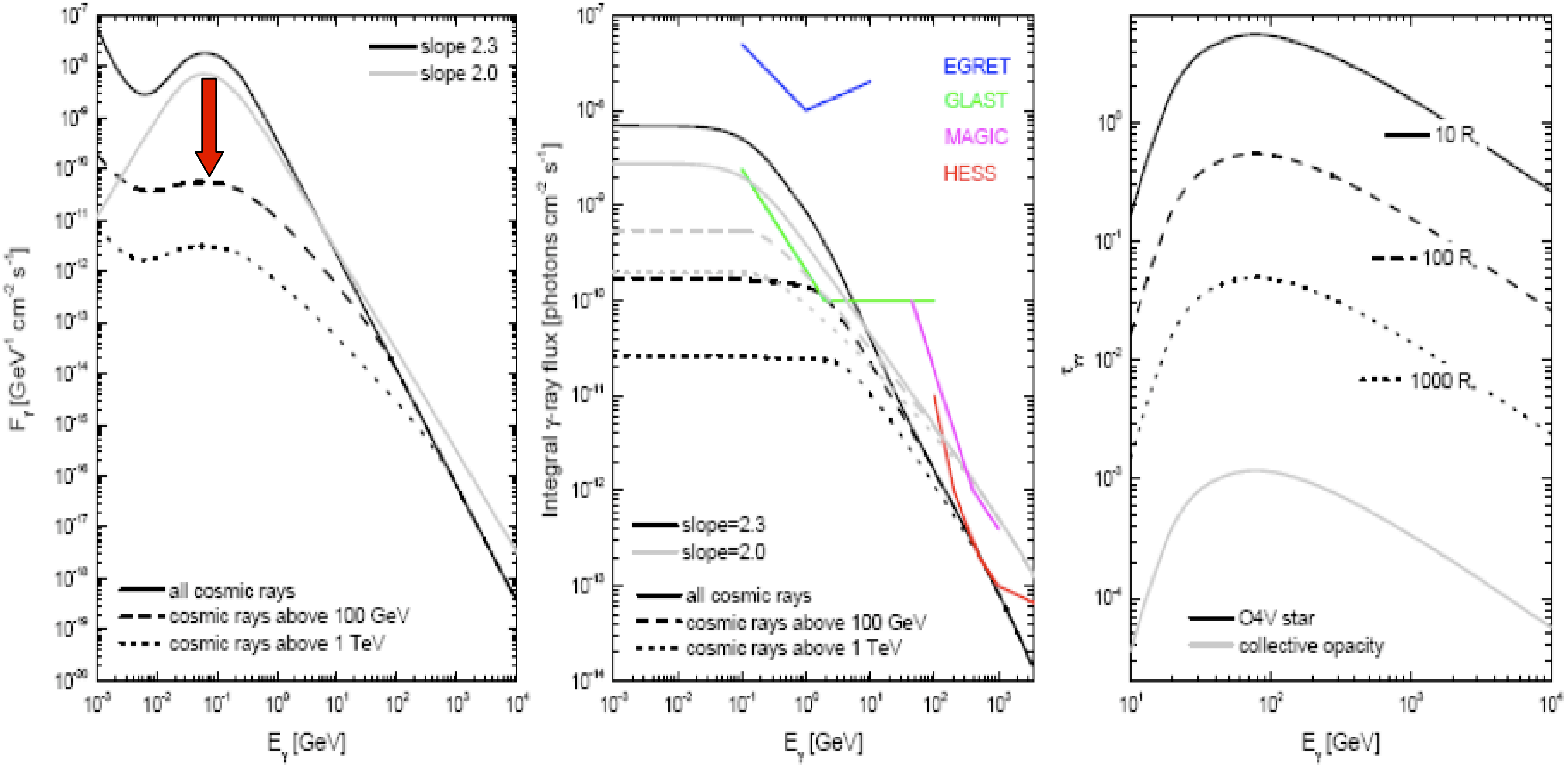


Fig. 1. Known and expected extragalactic nonthermal sources of gamma rays (indicated by γ) and connecting physical processes (encircled by ellipses) in a simplified schematic form. The emphasis is on starburst galaxies and galaxy clusters, and the main topics of the paper are shaded. Apart from topological defects as possible relics from the big bang, and active galactic nuclei (AGNs), star formation in galaxies is the underlying process. In contemporary late type galaxies (at redshift $z \simeq 0$) matter mainly cycles between stars and the cool interstellar medium (ISM) through Supernova (SN) explosions and stellar winds (SWs). However in starbursts, due to contemporary or protogalactic (at $z > 1$) collisions, a very high pressure hot ISM is produced in SN remnants (SNRs), with comparable energy release in Cosmic Rays (CRs). Especially in clusters, galactic winds then play a central role in removing mass and in heating the external medium. They may be the strongest sources of extragalactic nonthermal particles over the history of the Universe.

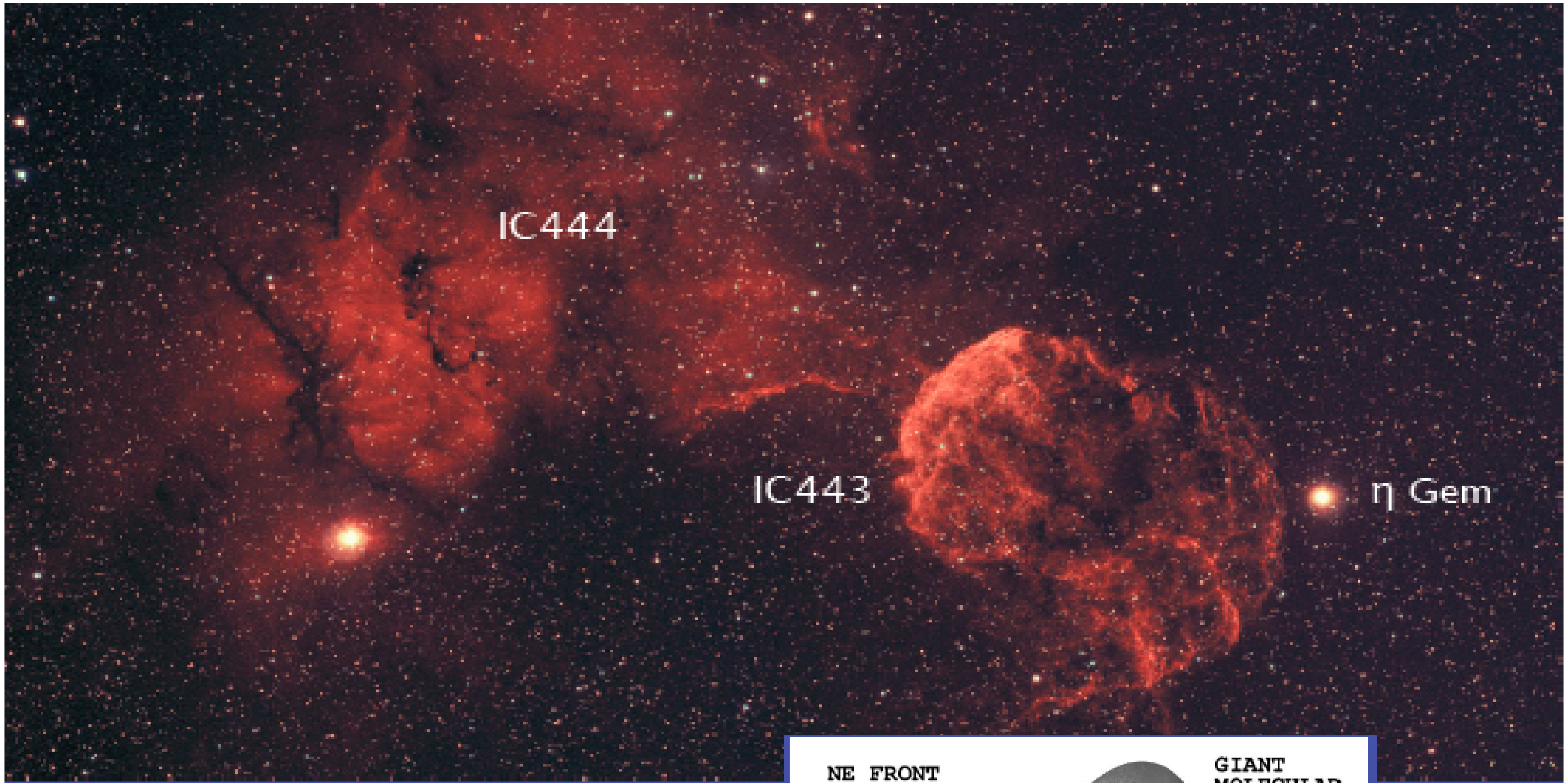
Collective massive star winds



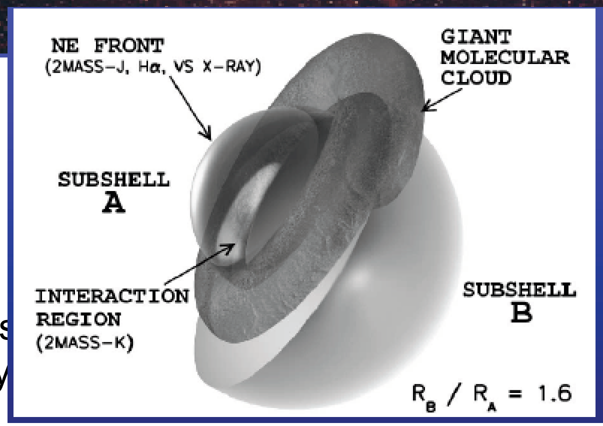
Domingo-Santamaria & Torres'06

- Lower energy (100 GeV/1 TeV) particles are excluded by the wind modulation effect.
- 10-100 GeV radiation may be absorbed by pair production close to the stars.
- To be scaled with the cluster distance, power and age.

IC443 SNR (example of SNR/Molecular cloud interaction)



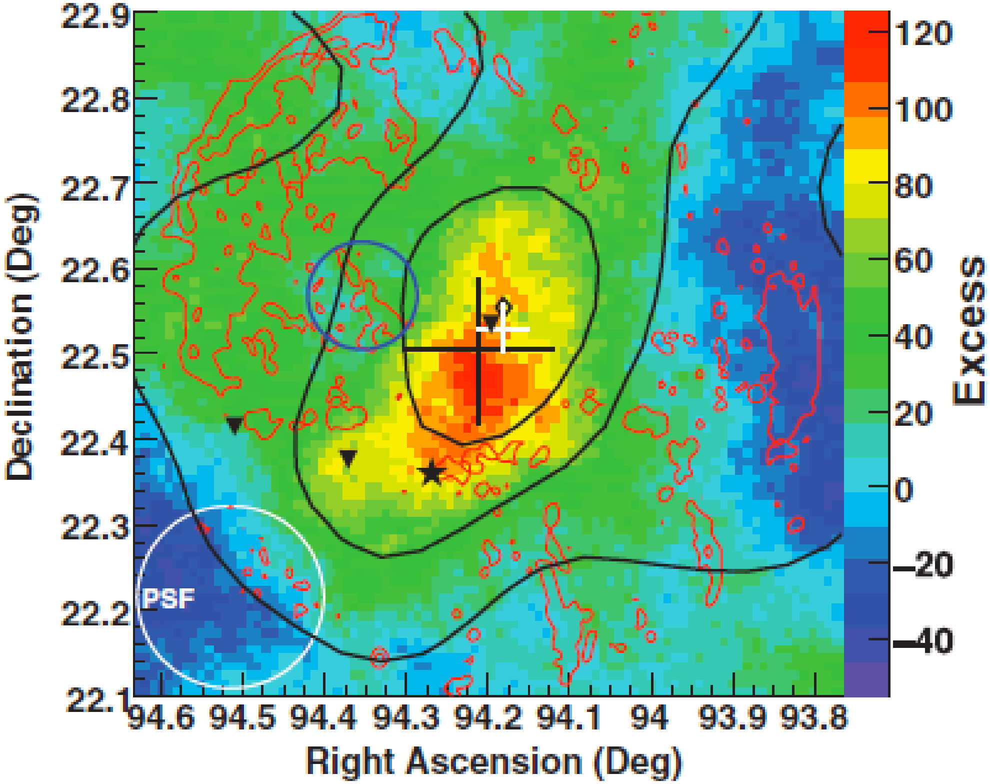
H_α Troja et al'06

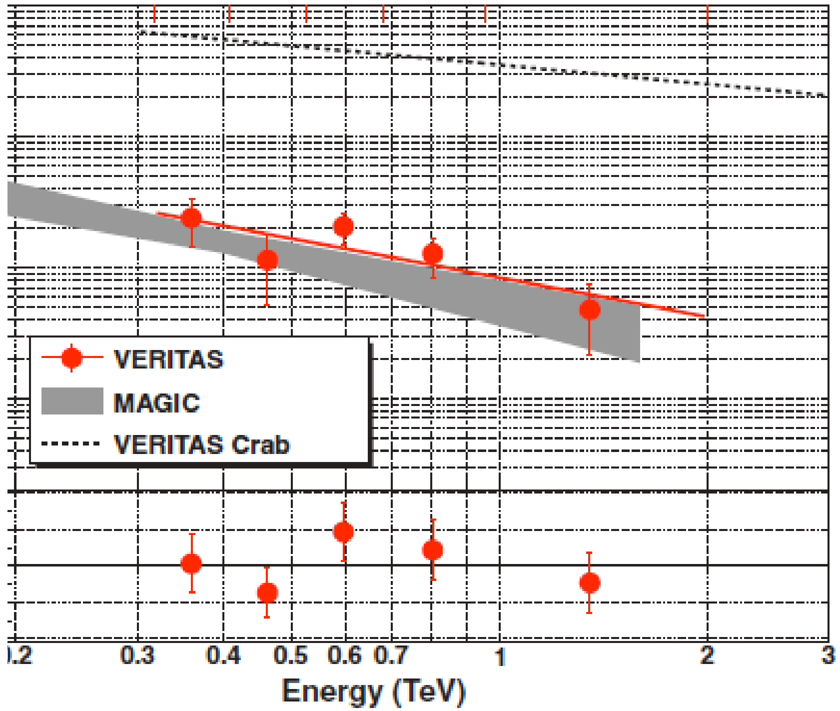


Age ~30 000 years
Distance ~1.5 kpc

IC 443 in gamma-rays

Veritas excess map

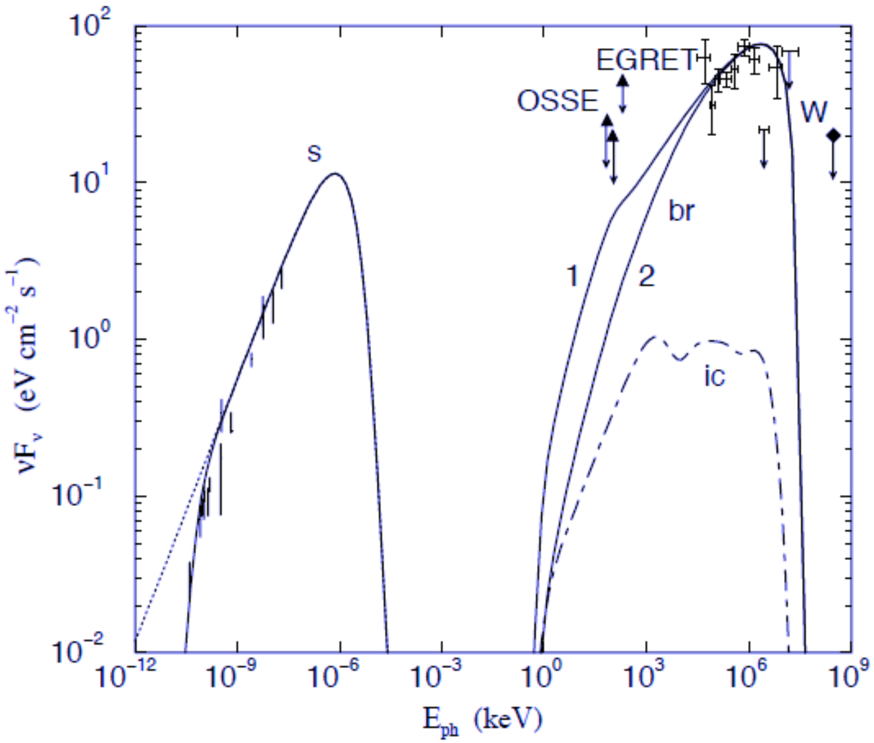




White cross: Magic
Black cross: Veritas + PSF in white
Open blue circle: 95% confidence contour Fermi (Abdo et al'09)
Triangles OH masers
Black contours CO data
Red: optical
Black star: PWN

MAGIC: Albert et al'07
VERITAS: Acciari et al'09

SNR/Molecular cloud interaction



IC 443

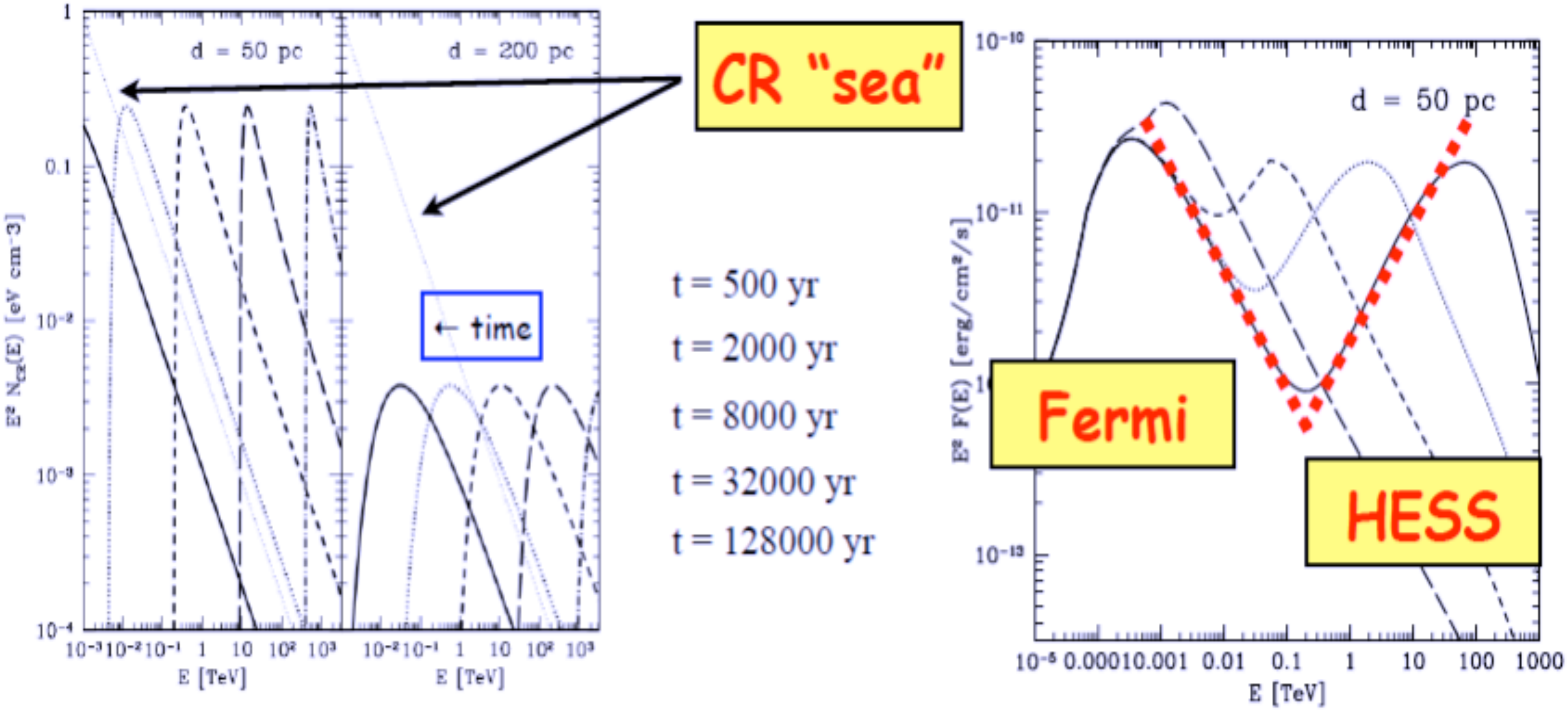
* Injection from thermal pool at the shock front (Bykov et al'00)

* Min energy electron reacceleration (stochastic)
1/ E=120 keV 2/ E=2 GeV

• No strong TeV radiation expected
  - Low velocity (~100 km/s) shocks
  - Wave absorption by ion-neutral damping.

* TeV radiation from illumated clouds ? (Gabici et al'07)

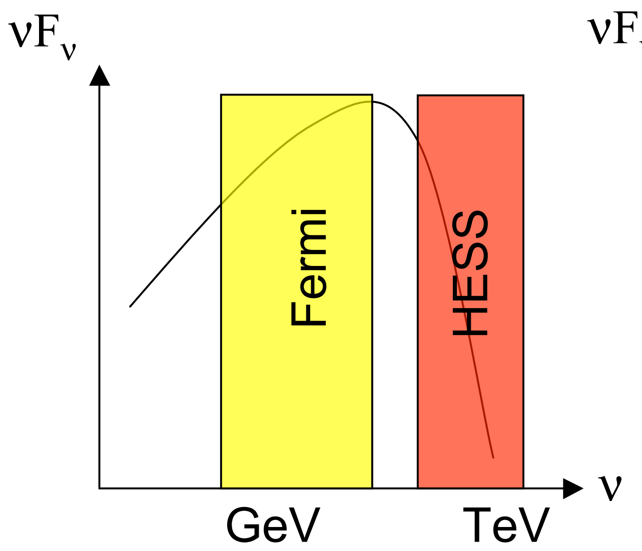
“Passive” cloud radiation

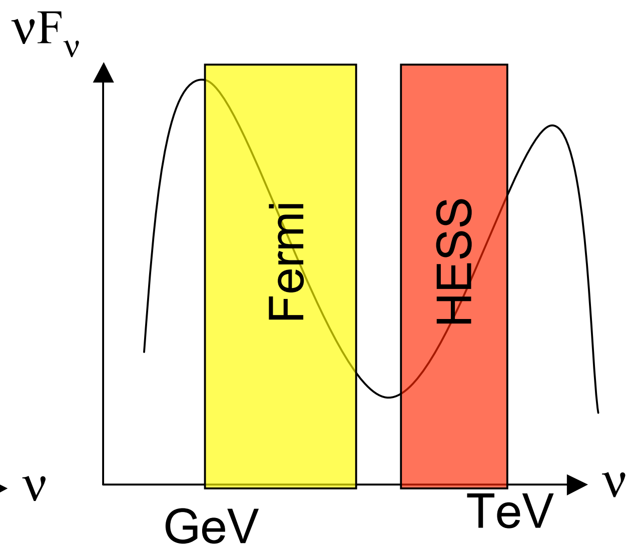


Gabici et al’09

=> Cosmic Rays

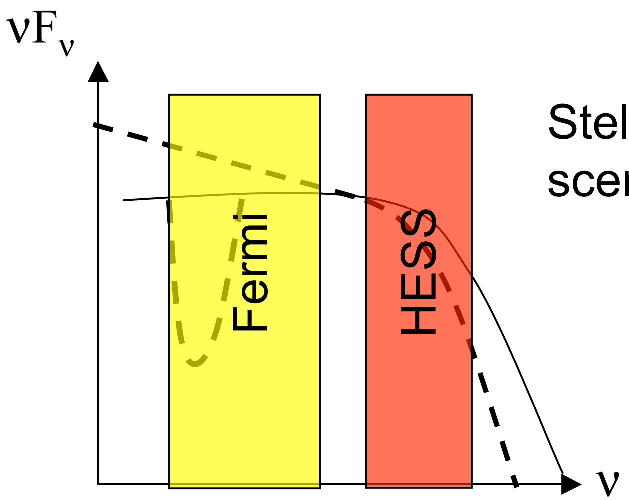
Spectral signatures GeV-TeV





SNR/MC scenario

CR spectrum



Stellar wind scenario

SB/supershell scenario